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A scoping study on

Climate change and hydropower in the Mekong River Basin: a synthesis of research

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Climate change and hydropower in the Mekong River Basin: a synthesis of research

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1 INTRODUCTION

The Mekong is a vast trans-boundary river, shared by six countries—China, Myanmar, Laos, Thailand, Cambodia, and Vietnam (Figure 1). From its origin on Tibetan Plateau at 5200m above sea level to its discharge into the South China Sea through the distributary channels of the Mekong Delta, the Mekong flows 4350 km (the world's 12th longer river), drains a 795,000 km^2 catchment, and has the eighth largest annual discharge volume (475 km^3) among the world's rivers (MRC 2010). The annual hydrological cycle of the Mekong is driven mainly by the regional monsoon climate, resulting in a very regular annual flood pulse during the wet season months of July through September. This flood pulse gives rise to significant ecological services and values, especially in the large floodplains of Cambodia and Vietnam (e.g. Junk et al. 2006; Kummu et al. 2006; Lamberts and Koponen 2008), sustaining high aquatic ecosystem productivity (e.g. Poulsen et al. 2004; Lamberts 2006) and supporting livelihoods for a substantial proportion of the people living in the basin (e.g. Keskinen 2006; MRC 2010).

In recent decades, Mekong River Basin (MRB) countries have experienced rapid economic growth accompanied by increasing demand for electricity. Hydropower is recognized by government decision-makers as an important source of energy for the Mekong region and its population. More than 170 hydropower dams are in operation, construction, or planning for the mainstem Mekong and its tributaries.

In the coming decades, however, the MRB is likely to experience significant impacts of global climate change that have serious implications for regional hydropower development as well as for the people and wildlife that depend on the natural flood pulsing of the Mekong system. Globally, climate warming observed over the past several decades is consistently associated with a range of hydrological changes, affecting not only temperatures but also precipitation patterns, intensity and extremes, rates of snow and ice melting, atmospheric water vapor, evaporation, soil moisture, and runoff (Bates et al. 2008). The frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) has likely increased over most areas. The area of land classified as very dry has likely more than doubled since the 1970s. There have been significant decreases in water storage associated with mountain glaciers and Northern Hemisphere snow cover. Shifts in the amplitude and timing of runoff in glacier- and snowmelt-fed rivers, and in ice-related phenomena in rivers and lakes, have been observed. The significant natural variability in all components of the hydrological cycle, from inter-annual to decadal time-scales, likely mask additional long-term trends.

Southeast Asia will be particularly hard hit by climate change. There is considerable evidence that climate change is already affecting the region (Christensen et al. 2007). Scientists of the Intergovernmental Panel on Climate Change (IPCC) report an increasing trend in mean surface air temperature in Southeast Asia during the past several decades, with a 0.1–0.3°C increase per decade recorded between 1951 and 2000. Rainfall has been trending down and sea levels up (at the rate of 1–3 millimeters per year), and the frequency of extreme weather events has increased: heat waves are more frequent (an increase in the number of hot days and warm nights and decrease in the number of cold days and cold nights since 1950); heavy precipitation events rose significantly from 1900 to 2005; and the number of tropical cyclones was higher during 1990— 2003. These climatic changes have led to massive flooding, landslides, and droughts in many parts of the region, causing extensive damage to property, assets, and human life. Climate change is also exacerbating water shortages in many areas, constraining agricultural production and threatening food security, causing forest fires and degradation, damaging coastal and marine resources, and increasing the risk of outbreaks of infectious diseases. As future temperature increases become nonlinear and more rapid (Christensen et al. 2007), these climate change impacts are projected to be correspondingly much more severe (Salim2009).

But while there has been substantial research undertaken on climate change impacts in the Mekong region[1], few studies have considered the impact of climate change on hydropower development in the MRB, nor the relative benefits and costs of hydropower development as a means for mitigating climate change impacts. This report, commissioned by the MRC-GIZ Cooperation Programme, provides a review of available literature related to climate change, hydrological processes, and hydropower development specific to the MRB, as well as other river basins of relevance and applicability to the MRB. We provide an overview of the climate and hydrology of the MRB, and a synthesis of knowledge and uncertainly about the impact of climate change in the region (Chapter 2). We assess the impact of climate change on existing and potential hydropower development in the MRB, and the gaps in knowledge and lessons learned from global studies of the impact of climate change on hydropower production (Chapter 3). We evaluate the role of MRB hydropower development in mitigating climate change impacts, through a reduction in Global Greenhouse Gas (GHG) emissions relative to fossil fuel-based energy sources, and the management of reservoirs to reduce the impact of extreme floods and droughts (Chapter 4). We also consider the potential for hydropower development to worsen climate change impacts, through the cumulative effects of river regulation and climate change on the ecological services and livelihoods supported by the Mekong River (Chapter 5). Finally, we provide recommendations for further research, modeling, and monitoring to fill gaps in knowledge of critical importance to political leaders, hydropower developers and operators, the Mekong River Commission, and other stakeholders (Chapter 6).

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[1] The electronic supplementary material to Lacombe et al. (2012) includes the most recent literature review of previous climate change studies in the Mekong (http://link.springer.com/content/esm/art:10.1007/s10584-011-0359-3/file/MediaObjects/10584_2011_359_MOESM1_ESM.doc).

National Geographic, Esri, DeLorme, NAVTEQ, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC

Figure 1. The Mekong River Basin in Southeast Asia.

2 IMPACT OF CLIMATE CHANGE ON MEKONG RIVER BASIN HYDROLOGY

The extensive work of the IPCC includes assessment of the impact of climate change on water resources (Kundzewicz et al. 2007), and a technical paper on climate change and water (Bates et al. 2008). These exhaustive peer-review reports, and the numerous studies they cite, provide an important foundation for understanding the impact of climate change on river basins. Additional studies have analyzed changes in climatic variability as it relates to key hydrological processes in the MRB (e.g., Delgado 2010, Delgado 2012, Rasanen, T. A. and M. Kummu 2012, Rasanen et al. 2012, Rasanen et al. 2013, Lacombe et al. 2012, Lacombe et al. 2013), and modeled the impact of climate change on the Mekong system hydrology Snidvongs et al. 2003, Hoanh et al. 2003, Eastham et al. 2008, Mac Sweeney et al. 2008, TKK and SEA START RC 2009, Salim 2009, Johnston et al. 2010, Hoanh et al. 2010, MRC 2011a, Vastila et al. 2010, Kingston et al. 2011, Lauri et al. 2012), based on different assumptions about the future of the basin.

This section provides an overview of the hydrology of the Mekong River Basin, and provides a synthesis of knowledge about the specific impact of climate change on Mekong river basin hydrology, and assesses gaps in that knowledge of relevance to our overall assessment of the impact of climate change on the future of Mekong River Basin hydropower development.

2.1 Overview of climate and hydrology

The Mekong River Basin (MRB) is often divided into the Upper Mekong Basin (UMB) and the Lower Mekong Basin (LMB). The UMB of China and Myanmar (24% of the total basin area) includes three physiographic regions--the Tibetan Plateau, the Three Rivers region, and the Lancang[2] Basin (Figure 2). The UMB is characterized by high mountains, steep slopes, deep gorges, and narrow catchment areas. The Mekong cascades down more than 4000m over a distance of 2000 km from its headwaters in China to Chiang Saen in northern Thailand, with an average slope of 2 m/km (Lauri et al. 2012). The LMB of Laos, Thailand, Cambodia, and Vietnam (76% of total basin area) includes the Northern Highlands, Khorat Plateau, Tonle Sap Basin, and Mekong Delta physiographic regions (MRC 2010) (Figure 2A). From Chiang Saen at China-Laos border to Kratie in central Cambodia, the Mekong has a moderately steep slope, falling about 500 m over a course of 2000 km, with an average slope of 0.25 m/km (Lauri et al. 2012). Further downstream the river is nearly flat, losing only 15 m in elevation over the final 500 km of the Mekong Delta region to the South China Sea (MRC 2005).

The MRB climate is dominated by regional monsoonal systems. The southwest monsoon produces a distinct wet season that begins in mid-May and continues through mid-October, during which time the basin receives 90% of its annual precipitation. Cyclonic disturbances may cause widespread rainfall of long duration during July to September, which can result in serious flooding. The northeast monsoon occurs from November to mid-March, producing a

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[2] The Upper Mekong River is referred to as the Lancang River in China.

cooler dry season with relatively low rainfall contribution. Mid-March to mid-May and late October are transitional periods with unstable wind speed and direction (Table 1).

Table 1. Monsoon seasons and transitions in the MRB (MRC and UNEP 1997).

Cold season			**Summer season**		**Rainy season**					**Cold season**	
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Northeast monsoon			**transition**		**Southwest monsoon**					**Northeast monsoon**	

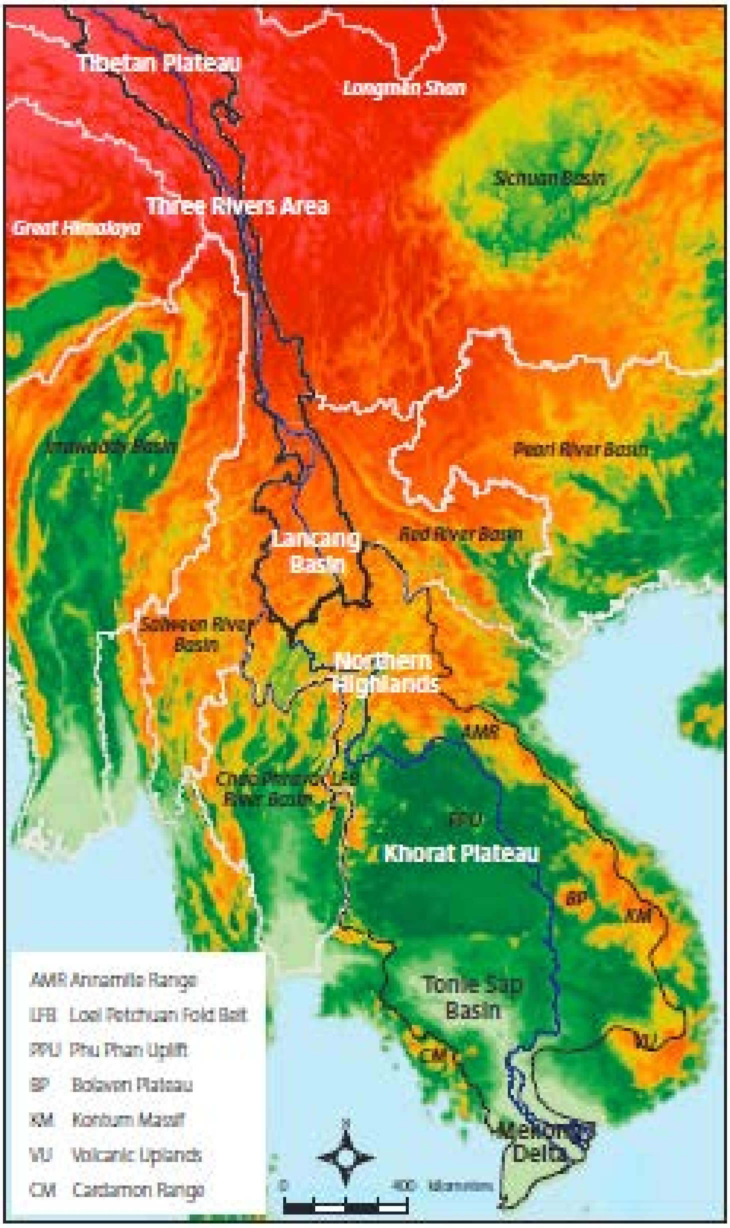

Figure 2. Topography and physiographic regions of the Mekong river basin (MRC 2010).

The climate of the UMB varies significantly from its headwaters to lower reaches. At the source in the Tibetan Highlands, the basin has an alpine climate with tundra and montane semi-desert land cover. Winter temperatures at Deqen, China, for example, fall below zero and summer averages may only reach 13° C (MRC 2005). Below the high plateau, the river flows south through temperate deciduous and evergreen forest of Yunnan Province, China. At Jinhong, China, 340 km upstream of the hydrological boundary with the LMB, the valley climate becomes sub-tropical with average summer temperatures only slightly cooler (2-3 °C) than the LMB Northern Highlands (MRC 2005). Evaporation in the UMB ranges from 1000-2000 mm, and is highly variable depending on altitude and slope orientation (MRC 2005).

The LMB has a tropical climate, with high heat and humidity. The minimum average monthly temperature is never lower than 20°C (MRC 2010). Mean annual evaporation across the region is about 1500 mm, and ranges from 1000 mm in the Northern Highlands in Laos to more than 2000 mm over the Khorat Plateau of northeast Thailand---one of the driest regions of Southeast Asia. Variability in evaporation is low from year to year due to the high relative humidity (MRC 2010).

Due to the strong regional influence of the monsoon system, the seasonal distribution of rainfall in the UMB and LMB is quite similar with distinct wet and dry seasons. Peak annual rainfall occurs during June-October. The distribution of rainfall in the UMB varies from north to south, and with elevation, from 1,600-1,700 mm in the mountains to 900-1,100 mm on the valley floor. Snow is rare in the valleys but increases significantly at higher altitudes and especially on the Tibetan Plateau, where most winter precipitation occurs as snowfall and rainfall is less than 600mm year (MRC 2010).

The distribution of mean annual rainfall over the LMB shows a distinct east to west gradient. The mountain regions of Laos receive the highest rainfall (>2500 mm/year), and the central regions of Thailand within the Mun–Chi Basin receive the least rainfall (<1000 mm/year). The greatest contributions to mainstream flows during the summer monsoon season thus originate within the large Mekong tributaries in Laos. Figure 3 shows the distribution and range of rainfall at selected stations across the LMB.

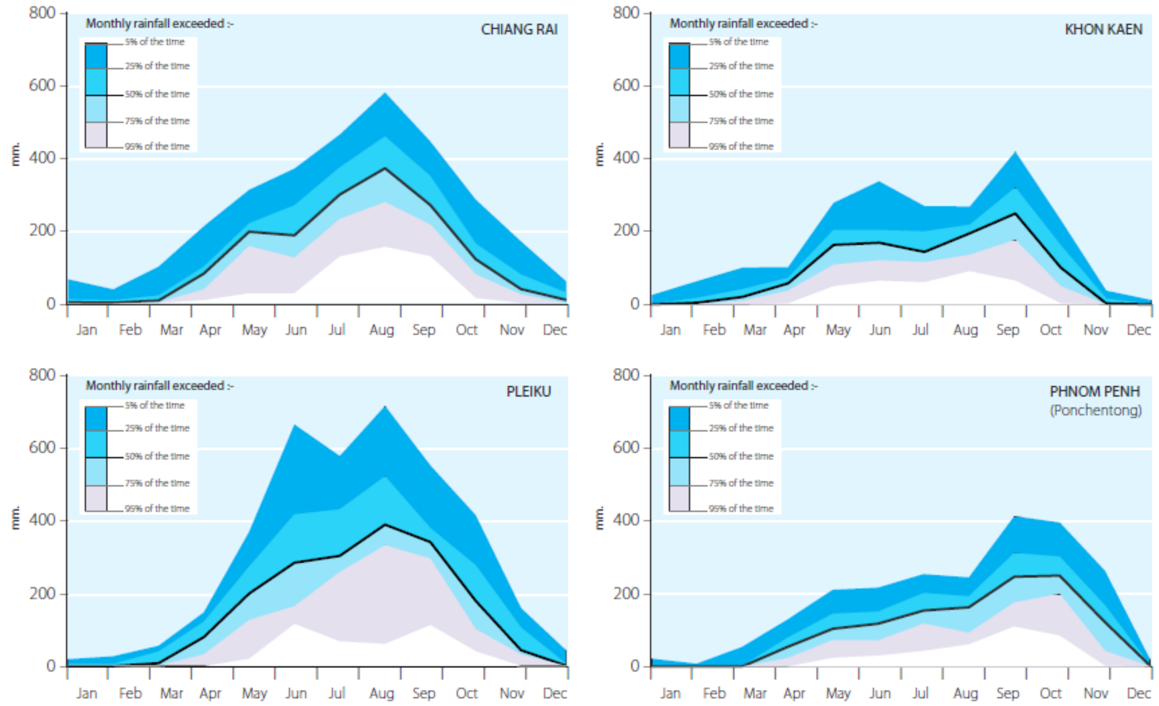

Figure 3. Monthly rainfall for LMB at selected stations (MRC 2010).

The hydrology of the MRB is largely controlled by snowmelt from the Tibetan plateau and monsoon rainfall-runoff from the tropical tributaries of Laos (Adamson et al. 2009).

The UMB contributes 15-20% (average 18%) of MRB annual flows (MRC 2005, Adamson et al. 2009). The Mekong is initially fed by melting snow in the Tibetan Highlands. Numerous studies of MRB hydrology consider snow storage and snowmelt to be important components of UMB runoff and dry season flows in the MRB (MRC 2005, Kiem et al. 2005, Adamson et al. 2009), although snow covers less than 5% of the Mekong Basin during November–March, and is negligible at other times. Recent studies by the Institute for Water Management Institute (*in press*) suggest the contribution of snowmelt may be relatively insignificant, other than in the highest reaches of the UMB, contributing less than 1% of total annual runoff. UMB rainfall drains rapidly through steep, narrow tributaries, with most catchments smaller than 1000km^2 (Adamson et al. 2009). UMB Runoff - whether sourced from snowmelt or groundwater baseflow-sustains dry-season flows in the northern portions of the LMB. UMB runoff also provides most of the floodwater during the majority of years. At Vientiane, for example, average contributions range from over 75% during the low-flow months in April-May, to over 50% during the peak-flow months of July, August, and September - although year-to-year contributions are highly variable (Adamson et al. 2009). Far downstream at Kratie, near the Tonle Sap confluence in Cambodia, the contribution of the UMB to Mekong flood-season flows is reduced to 15–20%, but the UMB still provides over 40% of the dry-season flow in April (Adamson 2006).

The LMB contributes 75-80% of MRB annual flows (MRC 2005, Adamson et al. 2009). The majority of LMB runoff is derived from the Mekong eastern riverbank tributaries of Laos that drain the high-rainfall areas of the Northern Highlands (Adamson et al. 2009) (Table 2). The larger western riverbank tributaries (mainly the Mun and Chi rivers) drain the low relief, lower rainfall regions of the Korat Plateau in northeastern Thailand, and contribute relatively little to mean annual discharge. In the flat, low-lying terrain of the Tonle Sap and Mekong Delta regions, flow contribution is minimal and water levels rather than flow volumes determine the movement of water across the landscape (Adamson et al. 2009). Figure 4 gives the average annual hydrographs for the Mekong basin at various gaging stations. Overall, the catchment of Laos contributes 43% of LMB runoff (and more than 35% of total MRB runoff), generating most of the wet-season peak discharge and significantly contributing to downstream flooding events (Adamson 2006). Thailand and Cambodia contribute 21-23% of LMB runoff, respectively, and the Vietnamese catchment contributes about 13%.

Table 2. Percentage flow contributions for mainstream reaches. Note the relatively large contribution from the eastern riverbank tributaries draining into the Nongkhai and Pakse reaches (MRC 2005).

River reach	Eastern riverbank (%)	Western riverbank (%)	Total (%)
China		16	16
China-Chiang Saen	1	4	5
Chiang Saen- Luang Prabang	6	3	9
Luang Prabang- Chiang Khan	1	2	3
Chiang Khan- Vientiane	0	0	0
Vientiane- Nongkhai	0	1	1
Nongkhai- Nakhon Phanom	19	4	23
Nakhon Phanom- Mukdahan	3	1	4
Mukdahan- Pakse	5	6	11
Pakse- Stung Treng	23	3	26
Stung Treng- Kratie	1	0	1
Total	60	16	100
	24		

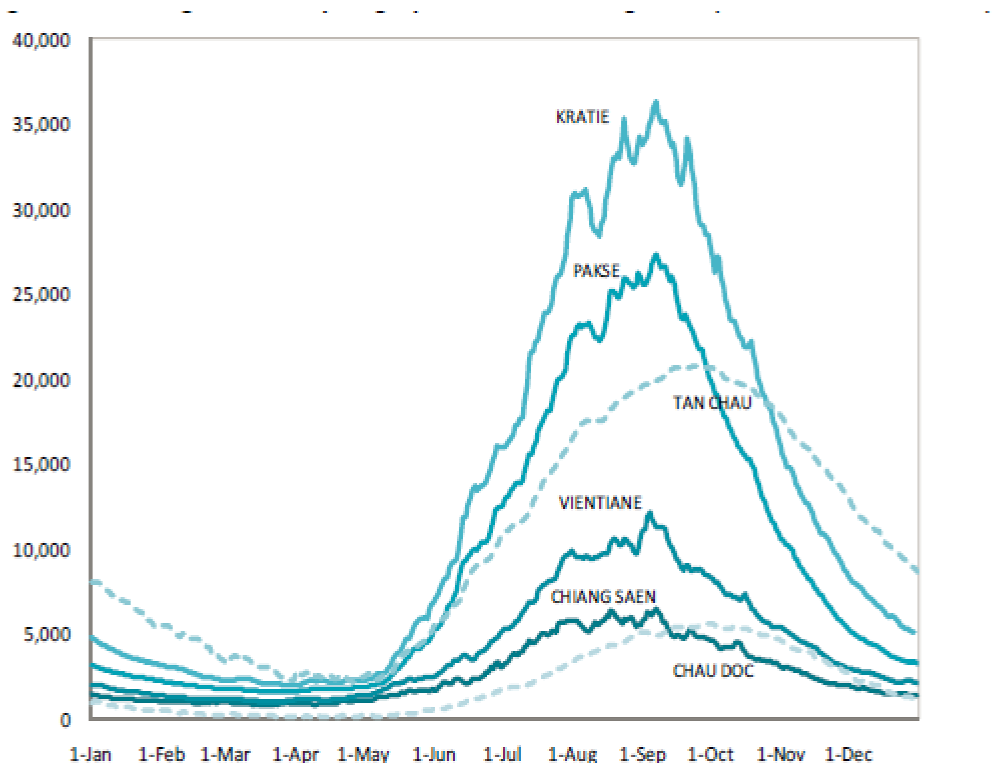

Figure 4. Average annual hydrographs for Mekong River Basin. Chiang Saen captures runoff from the UMB (about 65 km^3). Runoff increases to 350 km3 at Kratie, below which it enters the Tonle Sap floodplain of Cambodia (ICEM 2010).

The basin-wide influence of the monsoon climate and steepness of the Mekong river channel give rise to a single-peaked hydrograph, with large seasonal differences between high and low flows. The defining characteristics of Mekong River hydrograph, of particular relevance to assessing the influence of climate change and hydropower in the basin, are the regularity in the timing of the beginning and the end of the wet season; the single, smooth wet-season peak of consistent size and regularity, and the pronounced low-flow season (Adamson et al. 2009, MRC 2010, ICEM 2010).

Adamson (2006) divided the Mekong hydrograph into four distinct seasons over the hydrological year (Figure 5). The timing of the onset and the duration of these seasons is virtually identical for the UMB (measured at Chiang Saen) and LMB (measured at Kratie), as shown in Figure 4). The annual minimum daily discharge usually occurs in early April. The doubling of this discharge, generally in late May, defines the start of the first transition season (point 2). This ends when the flood season starts (point 3). The onset of the flood season (the point at which the discharge exceeds the mean annual discharge for that station) occurs within a few days each year at the end of June. The timing of peak flooding is very consistent over time, with a standard deviation of about 23 days. The second transition season defines the period between the end of the flood season (point 4) and the start of the dry (point 5), which occurs when rates of daily flow decrease become typical of “base-flow” recession. On average, the dry-season onset is in late November. The flood season lasts for just over 130 days. The fact that the start and end of the annual flood can be guaranteed to occur within a period of just 2 weeks is a remarkable and defining characteristic of the Mekong system (Adamson et al. 2009). As discussed in Chapter 5, the regularity of the seasonal onset and duration of flooding over the millennia has given rise to a biota that is finely tuned to these "predictable" hydrological conditions, and, consequently, a river system that likely is very sensitive to any changes in these characteristics resulting from climate change or river regulation (Adamson et al. 2009).

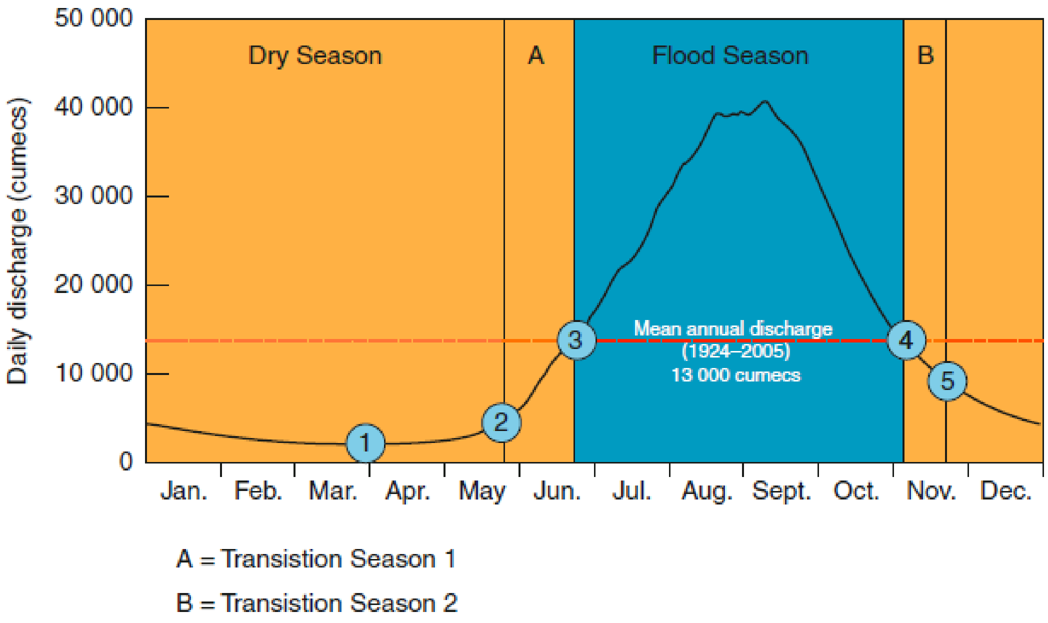

Figure 5. Mekong River average annual hydrograph with key transition seasons, with a single, smooth annual peak and prolonged period dry season flows (Adamson 2006).

Historically, cyclones and severe tropical storms have generated the most significant Mekong flooding events (Adamson et al. 2009). The largest recorded flood, in 1966, occurred when tropical storm Phyllis struck the UMB. At the downstream end of the basin, these severe tropical storms combine with the southwest monsoon to produce floods in Cambodia and the Mekong Delta (Adamson et al. 2009).

Pronounced dry season low-flows, sustained by UMB snowmelt and LMB baseflows, occur annually between November and May, and facilitate the seasonal transition from aquatic (flooded) to terrestrial (dry lands) environments (ICEM 2010). Groundwater resources in the Mekong River Basin have not been assessed comprehensively, but regional aquifers are considered to be substantial (MRC and UNEP 1997; MRC 2003; Eastham et al. 2008) and Hapuarachchi et al. (2008) noted shallow aquifers of recent alluvium 1-10 m deep flanking the mainstem Mekong river in Northeast Thailand.

2.2 Synthesis of knowledge and uncertainty about the impact of climate change on hydrology

Climate change will affect key hydrological parameters of relevance to hydropower generation in the MRB. Changes in temperature and precipitation patterns (including the volume, timing, and intensity of rainfall, and relative proportion of rainfall and snowfall) affect the timing, magnitude, and duration of river flows, the frequency of droughts and floods, the rate of evaporative water loss, the melting of glaciers, and the influx of groundwater for baseflows. Hydrological variability over time in a catchment is influenced by variations in precipitation over daily, seasonal, annual, and decadal time scales. Flood frequency is affected by changes in the year-to-year variability in precipitation and by changes in short-term rainfall properties (such as storm rainfall intensity). The frequency of low or drought flows is affected primarily by changes in the seasonal distribution of precipitation, year-to-year variability, and the occurrence of prolonged droughts (Snidvongs et al. 2003).

Climate change projections are derived from results of general circulation models (GCMs)[3]. Numerous GCMs now exist, dating back to the first models developed in the late 1960s at the NOAA Geophysical Fluid Dynamics Laboratory. Global climate change projections from these models are based on emission scenarios reflecting different development paths for the world. The Special Report on Emissions Scenarios (SRES) provides four storylines to describe the relationships between emissions driving forces, their evolution, and scenario quantification[4]. Each storyline represents different demographic, social, economic, technological, and environmental development pathways (Nakićenović et al. 2000).

Since 2003, many different GCMs have been applied to the MRB, encompassing development scenarios ranging from low (B1) to medium (B2, A1B) to high emissions futures (A2, A1FI) (Table 3). Early studies of the hydrological impacts of projected MRB climate change focused on climate forcings from individual GCMs using one or more development scenarios. Snidvongs et al. (2003), for example, tested the Australian Commonwealth Scientific and Industrial Research Organisation (CRISO) CCAM model, based on an atmospheric doubling of CO2 concentrations, and Hoanh et al. (2003) tested the U.K. Hadley Centre for Climate Prediction and Research HadCM3 model using high (A2) and moderate (B2) emissions scenarios.Other hydrological studies used the mean climate change projection from multiple GCMs. Ruosteenoja et al. (2003) assessed the results of

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[3] A general circulation model (GCM), also often known as a Global Climate Model, is a mathematical model of the general circulation of a planetary atmosphere or ocean. These equations are the basis for complex computer programs commonly used for simulating the atmosphere or ocean of the Earth. Atmospheric and oceanic GCMs (AGCM and OGCM) are key components of global climate models along with sea ice and land-surface components. GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change (http://en.wikipedia.org/wiki/General_circulation_model).

[4] The SRES climate change storylines cited in this report include scenarios of low population growth coupled with very rapid economic growth (A1), high population growth coupled with slower economic growth (A2), low population growth coupled with introduction of clean, resource-efficient technologies (B1), and moderate population growth and economic development (B2). The A1 scenarios are further sub-divided with respect to global use of energy resources, and include fossil intensive (A1FI), non-fossil intensive (A1T), and balanced fossil and non-fossil (A1B) futures. These six scenarios can be grouped according to their relative levels of future greenhouse gas (GHG) emissions:

- Low emission scenarios: B1, A1T
- Medium emission scenarios: B2, A1B
- High emission scenarios: A2, A1FI

seven GCMs over the next century for Southeast Asia, using multiple scenarios (A1FI, A2, B1, and B2). Mac Sweeney et al. (2008) assessed the means of 15 GCMs for 1970-2090 for the MRB, using scenarios A2, A1B, and B1. Eastham et al. (2008) used the median of 11 GCMs with one scenario (A1B) to project the 2030 MRB climate.

The main limitation to applying GCMs for hydrological studies of specific river basins such as the MRB is their large-scale resolution (typical GCM resolutions are between 1 and 5 degrees in latitude and longitude). Later studies downscaled the coarse GCM-based climate change scenarios to create higher resolution, limited-area models called Regional Climate Models (RCMs). The MRB RCMs have a spatial resolution of about 30-50 km that is suitable for input into hydrological models for impact assessment. TKK and SEA START RC (2009), Hoanh et al. (2010), Johnston et al. (2010), and Vastila et al. (2010) applied the PRECIS[5] Regional Climate Model (RCM), downscaled from the ECHAM4 GCM developed by Max Plank Institute for Meteorology in Germany. Lacombe et al. (2012) used rainfall and temperature output data from PRECIS to investigate MRB variability (trends in the long-term time series). Each study covered different development scenarios over different time periods.

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[5] PRECIS (Providing Regional Climates for Impacts Studies) is a regional climate model system developed by the Hadley Centre for Climate Prediction and Research, UK.

Table 3. Comparison of projected climate changes from major modeling studies (updated from Lacombe et al. 2012 and Johnston et al. 2010)

Authors	Snidvongs et al. 2003	Hoanh et al. 2003	Ruosteenoja et al. 2003	TKK and SEA START RC 2009	Eastham et al. 2008	Mac Sweeney et al. 2008a,b	Salim 2009	Johnston et al. 2010	Hoanh et al. 2010
Location	LMB	MRB	Southeast Asia	LMB	LMB	Cambodia, Vietnam	Thailand, Vietnam	Greater Mekong Sub-region	MRB
Models	CCAM	HAD CM3	7 GCMs	ECHAM4-PRECIS	11 GCMs	15 GCMs	MAGICC (GCM)	PRECIS/ ECHAM4	PRECIS/ ECHAM4
Scenarios	Not specific	A2, B2	A1F1, A2, B1, B2	A2	A1B	A2,A1B, B1	A1F1, B2	A2, B2	A2, B2
Period	Doubling of [CO2]	1960-2099	1961-2095	1960-2099	1976-2030	1970-2090	1990-2100	1960-2049	1985-2050
Projected changes in annual rainfall	Not explicitly quantified	-1.64 to +4.36 mm/yr	Either >0 or <0, depends on models and scenarios. Almost always insignificant.	Increase (not explicitly quantified)	+0.1 to +9.9 mm/yr	+0.3 to +0.6 mm/yr	1990-2050: +1.26 to -1.62 mm/yr (B2); 0.66 to -1.14 mm/yr (A1F1) 1990-2100: +3.27 to +4.91 mm/yr (A1F1) and -1.63 to -2.45 mm/yr (B2)	No significant change at the whole GMS scale	+1.2 (B2) to +2 (A2) mm/yr
Changes in seasonal rainfall pattern	Dry season drier and longer 1-month delayed Rainy season		Dry season drier and longer 1-month delayed rainy season	Dry season drier and longer 1-month delayed rainy season	Wetter rainy season (+1.7 to +6.1 mm/yr) Drier dry season (-0.3 mm/yr; not significant)	Wetter rainy season: +0.8 to +1.5 mm/yr (Cambodia); +0.4 to +1.5 mm/yr (VN) Drier dry season: -0.7 to -0.1 mm/yr (Cambodia); -0.3 to -0.1 mm/yr (VN)		Wetter rainy season in North Mynamar and Gulf of Thailand (from +0.2 to+0.6 mm/yr) Drier dry season on both sides of Gulf of Thailand (-2.5 to -2.8 mm/yr)	Wetter rainy season: +1.2 (B2) to +1.5 (A2) mm/yr Wetter dry season in UMB +0.9 mm/yr and insignificant change in LMB
Temperature	+ 1^0 to +3^{0}C (over a 100-yr period)	+0.026^0 to +0.036^{0}C/yr	+0.01^0 to +0.05^{0}C/yr	Increase (not explicitly quantified)	+0.012^0 to +0.014^{0}C/yr	0.00^0 to +0.06^{0}C/yr	+0.03^0 to +0.06^{0}C/yr	+0.03^0 to +0.06^{0}C/yr	+0.02 to 0.023^{0}C/yr

In the following section, we review the projected changes in different climate parameters resulting from various climate change models and assumptions about future development, and the impact of these changes on key hydrological parameters for the MRB. We emphasize the most recent model simulations, which are considered by the IPCC to be more reliable than earlier studies due to advances in knowledge, processes and feedbacks, and higher spatial resolution. We focus especially on climate change predictions over the next 30-40 years, the financial-planning time horizon that is of most relevance to MRB decision-makers and developers[6]. Lauri et al. (2012), citing MRC (2009a) and Kummu et al. (2010), note that the great majority of planned dams are expected to be operational by 2030. We also note longer term projections that correspond to the expected life of a hydropower project (typically the 2080s).

2.2.1 Temperature

Relatively small changes in temperature can have a profound effect on river basin hydrology. There is considerable evidence that daily, seasonal, and annual temperature patterns are already changing in Southeast Asia (Christensen et al. 2007). Over the past 3-5 decades, trends of increasing mean annual temperature have been recorded for the MRB as a whole and in each LMB country, mirroring that of global studies. Most notable is the increase in temperature variability from year to year (ICEM 2010).

According to IPCC (Christensen et al. 2007) projections, the mean surface air temperature in Southeast Asia will increase between 0.75–0.87°C by 2039, 1.32–2.01°C by 2069, and 1.96–3.77°C by 2100, relative to baseline conditions, depending on which baseline development scenario is assumed. This translates to an annual increase of 0.02-0.03°C per year across the region, closely matching observed rates of change for the period 1951-2000. While in most parts of Asia the greatest warming is projected to occur from December to February, future warming is projected to be stronger in Southeast Asia and spread throughout the year.

Projections of future temperature changes in the MRB vary according to the GCM model selected, assumptions about future development and GHG emissions, and the time period modeled, but are consistent among studies in showing a strong increase in future temperatures across the basin (Table 3). Lacombe et al. (2012) suggest that temperature will increase by about 0.023˚C per year across the MRB. Snidvongs et al. (2003) forecast that LMB temperatures would increase 1–3 ˚C over the next century, based on a doubling of atmospheric CO2. Hoanh et al. (2003) projected an increase of 0.026-0.036˚C/yr between 1960 and 2099, for moderate (B2) and high (A2) emissions scenarios, respectively. Ruosteenoja et al. (2003), using a range of emissions scenarios, projected an increase of 0.01-0.05 ˚C/yr between 1961 and 2095. Eastham et al. (2008) predicted a basin wide temperature increase of 0.79˚C by 2030, based on the means of 11 models, with bigger increases (0.81˚C) associated with the colder catchments in the north of the basin and smaller increases (0.68 ˚C) associated with the southern, maritime areas. Hoanh et al. (2010) predicted a mean annual temperature rise ranging from 0.4 to 1.2˚C across the basin for the A2 emission scenario during the period 2010–2050, with the most significant increases expected in the UMB. Lauri et al. (2012) projected that daily average temperature for the MRB would increase by 0.8–1.4˚C using the A1B scenario,

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[6] Most models adopt a 30-year simulation period (1961-90) as the reference period and then calculate change fields for future 30-year periods, namely the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099) (http://www.ipcc-data.org).

and 0.6– 1.3˚C using the B1 scenario, for the period 2032–2042 compared to 1982–1992 baseline. The spatial distribution of annual average temperature increase was similar for all runs, with greater increases in the southern and northern parts of the basin.

Vastila et al. (2010) further projected that the number of annual hot days (maximum temperature above 33˚C) will increase and the number of annual cool days (minimum temperature below average daily minimum temperature under current climate) will decrease. The most pronounced effects are seen in the southern part of the LMB.

In summary, it is highly likely that temperatures are increasing and will continue to increase in the MRB due to climate change, with the most dramatic increases in the high altitude snowfields and glaciers of the UMB. Most of the uncertainty in the magnitude of expected temperature increase relates to the storyline scenario modeled. Figure 6 provides an example of the spatial distribution of projected temperature change across the MRB by 2050 relative to current baseline for high and moderate emissions scenarios.

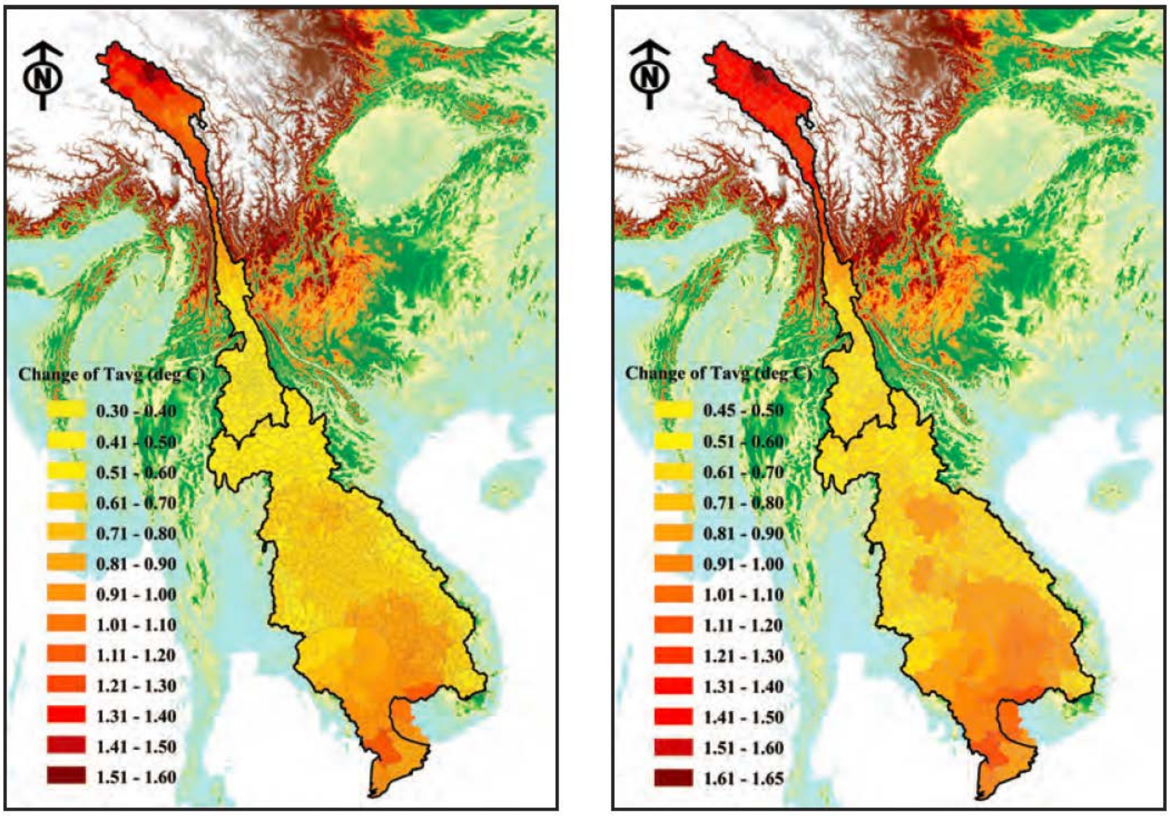

Figure 6. Projected increases in mean annual average temperature by 2050 relative to 1985-2000 baseline, for Scenario A2 (left) and Scenario B2 (right). Note that most substantial temperature increases are projected for the UMB, and lower reaches of the LMB (Hoanh et al. 2010).

2.2.2 Evaporation

Changes in open water evaporation and evapotranspiration affect river flows, lake and reservoir storage volumes, soil moisture conditions, and groundwater levels. Evaporative water loss can offset small increases in precipitation and exaggerate further the effect of decreased precipitation on surface waters. Evaporative demand, or ‘potential evaporation’, is directly linked to changes in temperature, as well as solar radiation, atmospheric humidity, and wind speed. Climate change models summarized in Kundzewicz et al. (2007) suggest increases in potential evaporation across the globe as the water-holding capacity of the atmosphere increases with higher temperatures while relative humidity remains relatively unchanged (Trenberth et al. 2003). As a result, open water evaporation is projected to increase, with the spatial variations in evaporative water loss related to spatial variations in surface warming. Changes in plant evapotranspiration are more complex (Bates et al. 2008), due to changes in plant physiology associated with increasing atmospheric CO2 concentrations. Experimental studies (e.g., Triggs et al. 2004) and global modeling studies (e.g., Leipprand and Gerten 2006; Betts et al. 2007) suggest reduced rates of evapotranspiration, only partially offset by increased plant growth. Gedney et al. (2006) attributed an observed 3% rise in global river discharges over the 20th century to CO2-induced 5% reduction in evapotranspiration, although these findings are inconclusive due to uncertainties in the changes in precipitation and other factors.

In the MRB, potential evaporation is projected to increase in all months and all catchments by 2050, consistent with global studies and regional trends in projected temperatures. Eastham et al. (2008) estimated a 30 mm (+2%) increase in annual potential evaporation across the basin in 2030 relative to baseline, with high certainty. Johnston et al. (2010) predicted that higher rates of potential evaporation associated with climate change will increase water demand of crops and pastures in both rainfed and irrigated systems of the MRB. Lauri et al. (2012) projected a significant increase in MRB evaporation/ evapotranspiration, using a variable leaf area index that increases for warm conditions when water is available and decreases in cold and/or dry conditions.

In summary, limited regional studies supported by substantial global modeling suggest it is highly likely that water loss due to open water evaporation, and to a lesser extent evapotranspiration, will increase in the MRB resulting from rising temperatures. The magnitude of water loss in each physiographic region will vary according to differences in geography and climate. Further research and monitoring is needed to clarify the magnitude of change, as the potential impact on the depth and volume of water in reservoirs, natural lakes, and wetlands of the MRB is significant.

2.2.3 Precipitation

Climate-change driven changes in the mean, variance, and seasonality of precipitation have profound implications for the hydrology and water resources of the MRB. Although temperature and evaporation show clear and consistent trends for different models and scenarios, the magnitude and direction of observed and predicted changes in precipitation associated with climate change in the MRB are unclear and inconclusive (e.g., Kingston et al. 2011).

Mean annual precipitation

Numerous studies of historic, observed MRB rainfall indicate a moderate increasing trend in mean climate over time, with a significant increase in rainfall variance over time (Delgado et al. 2010, Delgado et al. 2012, Rasanen et al. 2012, Rasanen et al. 2013, Lacombe et al. 2013).

Future projections for Southeast Asia, presented in the IPCC reports, suggest an overall average increase in mean annual precipitation by 2080–2099, relative to the 1980–1999 baseline period (Christensen et al. 2007). Ruosteenoja et al. (2003) found that projected changes in precipitation across Southeast Asia may be positive or negative, however, depending on which model and emissions scenario is selected. Similarly, Johnston et al. (2010) reported variable changes in rainfall with different GCMs, ranging from decreases of a few mm per year to increases of up to 30 mm with a high degree of uncertainty, for the six countries of the greater Mekong region.

MRB-specific studies by Hoanh et al. (2003) further support a variable response in rainfall across the basin depending on the scenarios modeled. They assessed the change of mean precipitation for the periods 2010-2039 and 2070-2099 relative to the 1961-1990 baseline, for a series of Mekong River sub-basins using moderate (B2) and high (A2) emissions scenarios. The projected trend in mean precipitation for 2039 varies across the different sub-basins from – 6% to +6% for each of the scenarios. By 2099, mean annual precipitation is projected to become more variable, ranging from -1.64 mm/yr to +4.36 mm/yr for the different sub-basins.

Other studies suggest an increase in precipitation that is consistent with, or exceeds, the IPCC projections, but with a high degree of spatial variability and uncertainty across the basin. Hoanh et al. (2010) projected an increase of 1.2–1.5 mm/year precipitation over the period 2010-2050. Figure 7 shows the percentage change in mean annual precipitation across the MRC sub-basins during 2010-2050 compared to that for the 1985-2000 baseline, for scenarios A2 and B2, respectively. Kiem et al. (2008) projected a 6.3% in precipitation by 2080-2099 relative to 1979-1988 baseline, using the Japanese Meteorological Agency GCGM2 model for the A1b scenario.

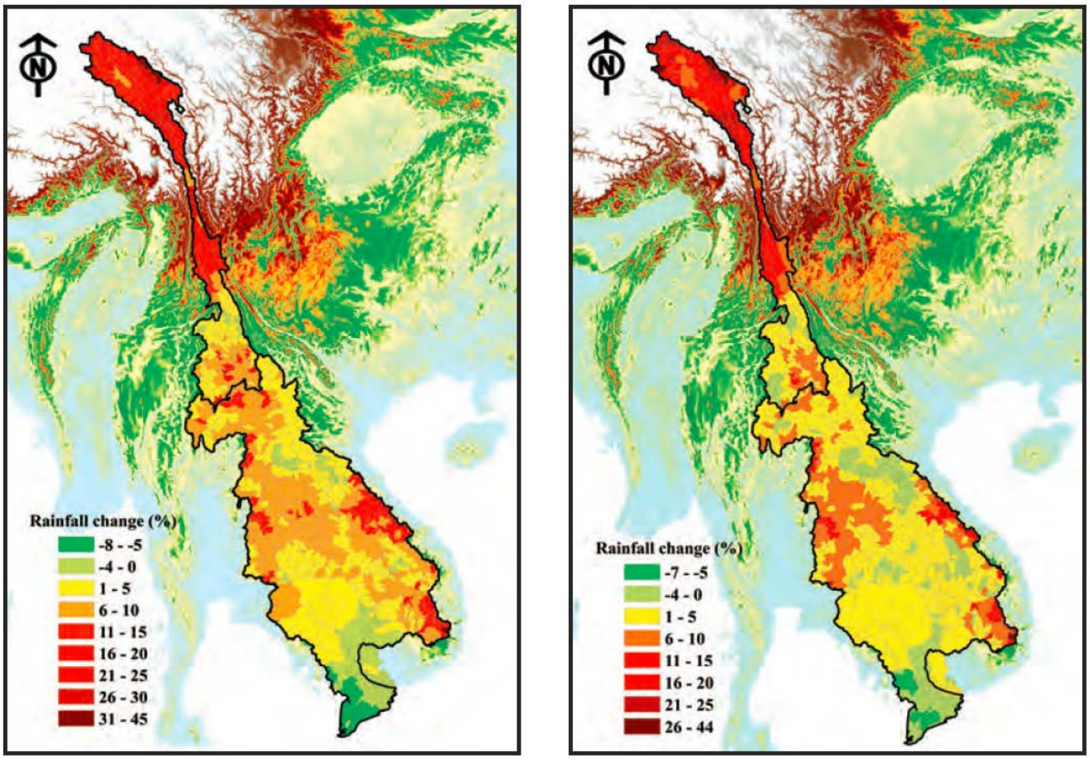

Figure 7. Change in mean annual sub-basin precipitation (%) during 2010-2050 compared to that for 1985-2000 for Scenario A2 (left) and Scenario B2 (right). Note the most substantial increases in precipitation are projected for the UMB and highland areas of the LMB, with decreasing precipitation projected for low lying areas and lower reaches of the LMB (Hoanh et al. 2010).

A multi-model study (Eastham et al. 2008) projected a more substantial increase in mean annual rainfall of 200 mm (13.5%) by 2030 for Scenario A1B based on the means of eleven GCM simulations. The study revealed a high degree of uncertainty in the magnitude of increase (30-360 mm) depending on the GCM used, and high spatial variability (ranging from 50-300 mm increase) across the different sub-basins of the MRB.

Most recently, Lauri et al. (2012) projected an increase in annual average precipitation for four of five downscaled RCMs. The spatial distribution of precipitation change across the basin differed more significantly among models than for temperature change. Using the A1B scenario, three models indicated that the middle part of the MRB would receive the largest increase of precipitation, whereas two models suggested that the largest increases are in the northernmost and southern parts of the catchment. The increase in precipitation ranges from 2.5-8.6 % (A1b) to 1.2-5.8% (B1).

Overall, it is likely that climate change will result in a modest increase in mean annual rainfall for the MRB as a whole, particularly in the UMB, over the next 30-50 years given that higher emissions scenarios project more significant increases in precipitation, and current observed emissions exceed even the high SRES scenarios (Christiansen et al. 2007). Year-to-year fluctuations in mean annual precipitation are likely to become more variable in the future (described further below). The magnitude of change in rainfall will vary significantly among the different physiographic regions as well. Further studies are needed to clarify the link between changes in precipitation processes (e.g. weakening or strengthening of the monsoon) and mean annual precipitation (Chapter 6). Vastila et al (2010) attributed the rise in annual rainfall to increased rainfall intensity during the rainy season (discussed further below), and decreases in rainfall have been attributed to a reduction of light rains during the dry season. Table 3 provides a comparison of projected changes in annual rainfall from selected climate change modeling studies.

Seasonal precipitation patterns

Adamson et al. (2009) note that the Tibetan Plateau plays a major role in the climate system of Asia and, in particular, upon the timing of the Southwest Monsoon system. Consequently, any thermal change on the plateau resulting from snowmelt and glacier retreat associated with global warming, could disrupt the pattern and intensity of the monsoon itself (Wu and Zhang 1998). Although there is no direct evidence of change in the onset and end of the monsoon season over the past 50 years (Adamson 2006, Johnson et al. 2010), there is growing consensus that the southwest monsoon will intensify and become more variable between years under climate change.

TKK and SEA START RC (2009), using the ECHAM4 climate model for the LMB, assessed changes in the seasonal pattern of rainfall between 1960 and 2099 for the A2 scenario. They project a drier, longer dry season and a one-month delayed onset to the wet season. These findings mirror those of Snidvongs et al. (2003) for the LMB and Ruosteenoja et al. (2003) for the whole of Southeast Asia. ICEM (2010) note that all MRB countries have experienced decreasing rainfall during the dry season with aggravated drought and water stress situations in many catchments.

Eastham et al. (2008) projected a variable response in dry season rainfall varies across the basin, from a 130 mm increase in the UMB to a 130 mm decrease in the south of the basin (including central and southern Laos, eastern Thailand, Cambodia and Vietnam). They predict an increase in wet season precipitation for all MRB catchments from an ensemble of GCMs, and an increasing disparity between wet and dry season precipitation in all sub-basins, particularly in the south where both decreases in dry season and increases in wet season precipitation are greatest.

Hoanh et al. (2010) predict wetter dry seasons will occur in the UMB with an increase of 0.9 mm/year, with no change in the seasonal pattern of LMB rainfall. Mac Sweeney et al.

(2008ac) predict a wetter wet season for Cambodia and Vietnam specifically. Johnston et al. (2010) suggest that time-lags in the seasonal patterns will likely result in a delay in the onset, the peak, and the end of the rainy season.

They project small, seasonal shift in rainfall, with drier dry seasons, and shorter, more intense wet seasons, and increases in the incidence of both droughts and floods for the Greater Mekong System (see below).

In summary, it is likely that the MRB will experience increased seasonality, with a shorter, wetter (and hence more intense) wet season and longer, drier dry season. The magnitude of the shift in seasonality depends on the GCMs and especially scenarios selected. Table 2C provides a comparison of projected changes in seasonal rainfall pattern from different climate change modeling studies.

2.2.4 Inter-annual variability and *exreme* events (floods and droughts)

A warmer climate, with its increased climate variability, increases the risk of floods and droughts (Wetherald and Manabe 2002; Christensen et al. 2007). Multi-model climate projections for the 21st century show increases in both precipitation intensity and number of consecutive dry days in many regions of the world (Christensen et al. 2007). Bates et al. (2008) noted that increased precipitation intensity and variability are projected to increase the risks of flooding and drought in many areas. The frequency of heavy precipitation events (or proportion of total rainfall from heavy falls) will be *very likely* to increase over most areas during the 21st century, with consequences for the risk of rain-generated floods. At the same time, the proportion of land surface in extreme drought at any one time is projected to increase (*likely*), in addition to a tendency for drying in continental interiors during summer, especially in the sub-tropics, low and mid-latitudes. Widespread increases in heavy precipitation events (e.g., above the 95th percentile) have been observed, even in places where total rainfall amounts have decreased. These increases are associated with increased atmospheric water vapor and are consistent with observed warming. Turner et al. (2007) suggested that the standard deviation of seasonal monsoonal rainfall totals could increase by up to 14%, leading both to larger floods and more extreme droughts.

Several studies link climate change in the MRB to an increase in observed extreme events, including seasonal shifts in monsoon weather patterns and increased floods and droughts. Christensen et al. (2007) note a significant increase in the number of heavy precipitation events in the MRB region from 1900 to 2005. Salim (2009) describes the Mekong floods of 2000 and droughts in Laos and Vietnam in 1997 and 1998 as examples of extreme events attributed to climate change. Kranz et al. (2010) suggest that the Mekong basin is experiencing an increase in water level variability and the intensity and occurrence of floods and droughts as result of climate change, noting that between August 2008 and February 2010 Vientiane experienced both the highest and lowest water levels on record for past five decades. Johnston et al. (2008) argue, however, that there is no convincing evidence that such events are outside of the range of “normal” climate variability, or that the frequency of such events has increased, at least in the mainland Southeast Asia. They argue that the reported increase in flood damage in the Mekong Delta should be attributed to demographic and land use changes, as increasing population has resulted in settlement of areas previously not used precisely because of their vulnerability to floods.

Projections of future increases in extreme events associated with climate change are more consistent among modeling studies. Eastham et al. (2008) predict increased flooding throughout the MRB by 2030 due to increases in extreme precipitation, with the greatest impact in downstream catchments on the Mekong mainstream due to the cumulative impact of increased upstream runoff. They project that the frequency of 'extreme wet' flood events in the LMB (measured at Kratie) is likely to increase from an annual probability of 5% under historic conditions to a 76% probability under this moderate emissions scenario. MRC (2010) suggest an increase in the incidence, depth, and duration of extreme events by 2050 coupled with an increase in the overall disparity between wet and dry seasons. Delgado et al. (2010, 2012) and Rasanen et al. (2012) report an increased likelihood of extreme floods and increased variance in the flows of the Mekong towards the end of 20th century, and that the levels of variance in the post-1950 period are unprecedented in at least the last 600 years (Lauri et al. 2012; Rasanen et al. 2013). These findings are supported by regional studies of climate change impact on river discharge. Milly et al. (2002), for example, projected that 100-year peak flow volumes will be exceeded more frequently in 15 of 16 large river basins worldwide. In some areas, the baseline 100-year flood is projected to occur much more frequently, perhaps every 2-5 years, albeit with a high degree of uncertainty (Kundzewicz et al. 2007). These impacts may be exacerbated by the increased frequency of tropical storms (discussed below) and sea level rise associated with climate change.

Relatively few studies have assessed the impact of climate change on the frequency of droughts in the MRB. Rasanen et al. 2013) analyzed MRB meteorological conditions over the period 1300–2005 using the Monsoon Asia Drought Atlas (MADA), a Palmer Drought Severity Index (PDSI) dataset derived from tree-ring growth records. They noted that MRB meteorological conditions varied historically at multi-annual, decadal, and centennial scales, and found two distinct features: multi-annual and decadal variation between prolonged wet and dry periods; and periods with higher or lower inter-annual variability between very dry and wet years. The variability in the post 1950 period is much higher compared to any of the other periods in the study.Several major drought events have occurred in the Mekong region over the past 20 years, including 1992, 1993, 1998 and 1999 (Adamson 2005). In 1993 and 1999 drought conditions resulted in water shortages for all major water users in Thailand. In 1998, severe drought in the Mekong Delta region of Viet Nam and Cambodia reduced the flooded area of the Tonle Sap to less than half of the typical season maximum of 15,000 km² (Te 2007).

The severity of drought conditions depends on the changes in the timing, duration and spatial extent of rainfall, as well as the total accumulated deficits in rainfall, streamflow, and soil moisture (MRC 2010). In 2004, total annual rainfall amounts were close to average throughout the MRB, but most rainfall occurred in the early parts of the wet season followed by an unusually prolonged dry season (MRC 2010). In northeast Thailand, no rain fell in the final three months of the year – the only time this has happened in the 55 years of rainfall records at Khon Kaen – resulting in regional crop failure, social hardship and economic losses (Adamson 2005).

Relatively few MRB-specific studies have assessed future changes in drought frequency for the MRB. Hirabayashi et al. (2008) project an increase in the number of drought days by 2100. MRC (2010) predict an increase in the seasonal irregularity of water availability due to increased frequency of droughts. These patterns concur with global projections, as noted above.

2.2.5 Tropical storms

Historically, the incursion of cyclones and severe tropical storms over the Mekong Basin from the South China Sea has played a major role in generating extreme flood events (Adamson et al 2009). Vietnam is one of the ten countries worldwide most at risk to increased frequency of tropical cyclones (Chaudhry and Ruysschaert 2007).

In a special report of the IPCC (1997), climate change in the MRB was directly linked to an increased number of tropical cyclones. Recent studies summarized in Cruz et al. (2007) indicate that the frequency and intensity of tropical cyclones originating in the Pacific have increased over the last few decades (Fan and Li 2005). These cyclones are responsible for a significant component of annual rainfall (MRC 2005), and changes in the patterns of storm activity could impact on rainfall and runoff distribution (Johnston et al 2010). The El Niño-Southern Oscillation (ENSO) has an especially important influence on the weather and inter-annual variability of climate and sea level, especially in the western Pacific Ocean and South China Sea around the MRB. MRC (2009b) indicated that an increase in temperature of sea surface may increase the intensity and incidence of typhoons during El Niño years. A 10-20% increase in tropical cyclone intensity for Southeast Asia is projected for a 2-4°C rise in sea-surface temperature (Knutson and Tuleya 2004).

2.2.6 Groundwater baseflow

Baseflows contribute a substantial proportion of mean annual flows in the MRB, especially during the dry season. Hapuarachchi et al. (2008) indicates that groundwater contributes 7% of mean annual flows and 35% of average low flow in the dry season.

The impact of climate change on the groundwater component of MRB hydrology has not been explicitly modeled, but is likely to affect groundwater recharge rates and levels through changes in temperature, potential evaporation, and precipitation. Groundwater systems generally respond more slowly to climate change than surface water systems, and translating changes in rainfall into changes in availability of surface and groundwater depends on a complex set of hydrological factors. Groundwater levels correlate more strongly with precipitation than with temperature, but temperature becomes more important for shallow aquifers and in warm periods (Kundzewicz et al. 2007).

2.2.7 Glacial runoff

The Himalayan glaciers feed seven of the Asia’s great rivers, including the Mekong, and ensure a year-round water supply for billions of people (WWF 1995). Glacial advance and retreat is a natural phenomenon that has occurred in response to shifting climatic conditions for millions of years. However, recent research suggests that the glacial cover of mountain regions worldwide has decreased significantly in recent years as a result of rapid warming trends (Wessels et al. 2001; Haeberli and Hoelzle 2001). In the short-term, glacial runoff is projected to increase due to warming temperatures. Observational evidence indicates that increased runoff and earlier spring peak flows are already occurring in many glacier and snow fed rivers (Kundzewicz et al. 2007, WWF 2005). In the long-term, warming will eventually result in reduced river flow in many river systems as glacial masses degrade and the contribution of glacier melt declines (Bates et al. 2008).

For the MRB, however, recent studies indicate that the impact of glacial melting on flow and water availability is likely to be insignificant both during the period of enhanced melting, and after the glaciers have ceased to exist (Eastham et al. 2008, Johnston et al. 2010, IWMI *in press*). The total volume of the glaciers within the MRB is about 17.3 km^3. Permafrost, which covers about 50,000 km^2 of the Tibetan part of the catchment, represents an additional 10 km^3 of ice[7] (Johnston et al 2010). In total, 27.3 km^3 of ice is equivalent to 25.0 km^3 of water. Assuming that all glaciers and permafrost completely disappear by 2030 as a consequence of global warming (an extreme scenario), and that melting occurs at a constant rate during the six warmest months of the year, the glacier melting would contribute about 80 m^3/s to Mekong discharge from April to September. This represents a negligible contribution to Mekong River discharge at Chiang Saen during this same period (3,500 m^3/s). Even if the estimated melting rate is substantially underestimated, the contribution of glacier melting to seasonal flows would remain insignificant (Johnston *et al.* 2010).

Although the impact of climate change on glacial melting is not expected to significantly alter the hydrology of the MRB, an earlier and reduced magnitude snowmelt-related seasonal flow peak is projected for the UMB by Kingston et al. (2011), who conclude that earlier snow melt caused by global warming is one of the most reliably predictable impacts of climate change on MRB river flow. Such changes would have important implications for high and low flows throughout the MRB, described below.

2.2.8 Mekong River discharge

Since the IPCC Third Assessment Report (2001), over 100 studies of climate change effects on river flows have been published in scientific journals, and many more have been reported in internal reports (Kundzewicz et al. 2007). Some global-scale assessments (e.g., Manabe et al. 2004a, b; Milly et al. 2005, Nohara et al. 2006) use climate models to directly simulate river runoff at a course scale. Most studies use climate model simulations based on the different emissions scenarios to feed basin-specific hydrological models. As noted in Kundzewicz et al. (2007), methodological advances since the IPCC (2001) have focused on exploring the effects of different ways of downscaling from the climate model scale to the catchment scale (e.g., Wood et al. 2004), the use of regional climate models to create scenarios or drive hydrological models (e.g., Arnell et al. 2003; Shabalova et al. 2003; Andreasson et al. 2004; Meleshko et al. 2004; Payne et al. 2004; Kay et al. 2006; Fowler et al. 2007; Graham et al. 2007a, b; Prudhomme and Davies 2007), ways of applying scenarios to observed climate data (Drogue et al. 2004), and the effect of hydrological model uncertainty on estimated impacts of climate change (Arnell 2005).

In large river basins such as the MRB, small changes in precipitation associated with climate change can result in substantial changes in river flow (Hapuarachchi et al. 2008). Temperature changes may also have a direct impact on the magnitude and seasonality of river flows where much winter precipitation currently falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing (Bates et al. 2008). Aerts et al. (2006) and Ward et al. (2007) suggest that climate change over the next century may have as large an impact on Mekong discharge as long-term natural climate variation over the past 9000 yr, and numerous studies have attempted to quantify this future MRB flow regime. As noted in the previous section, these modeling studies range from global assessments using a single GCM (e.g., Palmer et al. 2008) to single GCMs with multiple scenarios (Hoanh et al. 2003), to downscaled RCMs developed from a single GCM with multiple emissions scenarios (e.g., TKK and SEASTART RC 2009, Hoanh et al. 2010, MRC 2011a), to the mean of multiple GCMs (e.g., Eastham et al. 2008, Johnston et al.

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[7] Based on an average soil porosity of about 10% and maximum 2 m depth of frozen soil (Johnston et al. 2010).

2010), to a range of outcomes from an ensemble of GCMS (Kingston et al. 2011) and downscaled RCMs (Lauri et al. 2012) using multiple scenarios.

Palmer et al. (2008) conducted a global assessment of the effects of climate change on river discharge, and projected a 1% reduction in Mekong River discharge by 2050 relative to 1960-1990 baseline, based on the HadCM3 GCM using the high emissions scenario (A2).

Hoanh et al. (2003) used the HADCM3 GCM to project river flows under modest (B2) and high (A2) emissions scenarios, and estimated that maximum monthly flows in the LMB at Kratie will increase by 35-41% by 2099, relative to the 1961-90 baseline, and minimum monthly flows will decline by 17-24% in the basin. Maximum daily flow also are projected to increase significantly by 15-30% over this time period under the B2 and A2 scenarios, respectively. Their results strongly suggest an increased risk of flooding during the wet season and an increased potential for water shortage in the dry season.

Several studies using the PRECIS RCM downscaled from the ECHAM4 GCM project that climate change will lead to increased annual runoff and more variable conditions (Hoanh et al. 2010, MRC 2011a, Vastila et al. 2010). Hoanh et al. (2010) projected a 21% increase in total annual MRB runoff at Kratie by 2030, including a 5–11% increase in wet season flows and a 19–23% increase in dry season flows. Runoff increases are forecast for each of the sub-basins, primarily resulting from increased wet season runoff. Dry season runoff remains the same or to increase in 14 sub-basins, with small decreases in 4 other sub-basins. MRC (2010) predict substantial changes in MRB runoff, river discharge, and flooding, including a 15-21% increase in annual runoff by 2050 and 22% increase in flood duration in the delta region, based on a 13.5% increase in annual rainfall. The wet season LMB flow is predicted to increase by about 15% at Kratie; further downstream the estimated increase is lower due to the relatively smaller increase in precipitation. As with Hoanh et al. (2010) they project that dry season flow will also increase by 30% at Kratie. Mean monthly flow would increase in both the wet and dry seasons with most pronounced effects for the dry season in the UMB and most pronounced for the wet season in the LMB. Vastila et al. (2010) project a 10% increase in annual flows at Kratie, including a 7% increase in wet season flows and 8% decrease in dry season flows. They note that the magnitude of projected increases in LMB runoff and discharge depend on the baseline period selected for comparison. They generated annual LMB discharges at Kratie for the period 2030-2049, relative to two different baseline periods. Relative to the 1961-2000 baseline period, a relatively dry period, LMB discharges are on average 15% higher, with decadal maximum discharges on average 18% higher and the decadal minimum discharges on average 3% lower. Relative to a significantly wetter baseline period (1995-2004), the average annual discharge increased by only 4% for this period, with wet season discharges increasing by 5% and dry season discharges decreasing by 2%. The highest decadal discharge is on average 4% higher and the lowest decadal discharge is on average 6% higher than baseline.

Eastham et al. (2008) used the mean of 11 GCMs for the A2 scenario to project a 22% increase in Mekong flow by 2030, based on an average increase in rainfall of 0.2 m (13%). The outputs of the individual GCMs are highly variable, however, ranging from −2 to 82%.

Kingston et al. (2011) assessed uncertainty associated with GCM structure, based on two sets of climate change scenarios--the impact of a 2°C rise in global mean temperature on MRB discharge using seven different GCMs, and the analysis of progressive changes in global mean temperature from 0.5 to 6°C above the 1961–1990 baseline, using the HadCM3. The study reveals a relatively small but non-linear response of annual river discharge to increasing global mean temperature, ranging from a 5.4% decrease to 4.5%

increase. Changes in mean monthly river discharge are greater (from −16% to +55 %, with greatest decreases in July and August, greatest increases in May and June) and result from complex and contrasting intra-basin changes in precipitation, evaporation and snow storage/melt. Overall results are highly dependent on the GCM used, with respect to direction and magnitude, driven by differences in GCM projections of future precipitation. In contrast, there is strong consistency between GCMs in terms of both increased potential evapotranspiration and a shift to an earlier and less substantial snowmelt season. In the UMB, the temperature-related signal in discharge is strong enough to overwhelm the precipitation related uncertainty in the direction of change in discharge, with scenarios from all GCMs leading to increased river flow from April–June and decreased flow from July - August, as a result of earlier snow melting linked to climate change (Kingston et al. 2011).

Kingston et al. (2011) further note than when averaged over large areas such as the MRB or its sub-basins, neither high, low, nor mean annual river flow may respond in a linear way to increasing temperatures. The nonlinear changes to Mekong river flow are thought to be a consequence of contrasting response to increased temperature in different parts of the Mekong Basin (earlier snowmelt versus increased evapotranspiration), complicated by seasonally and spatially variable changes in precipitation. They note that similarly complex responses to projected climate change have also been found in studies of other rivers that also have a strong snowmelt component to annual discharge (e.g. Thorne 2010).

In a subsequent study (Thompson et al. 2013), the authors assessed GCM and hydrological model-related uncertainty in climate change projections of MRB discharge. They again investigated two sets of climate change scenarios, using three hydrological models. The first set (based on a 2 °C increase in global mean temperature, simulated using seven GCMs) projected considerable differences in discharge among GCMs, ranging from catchment-wide increases in mean discharge (up to 12.7%), decreases (up to 21.6% in the UMB), and spatially varying responses, linked to differences in projected precipitation. The second scenario set (based on increases in global mean temperature of 1–6 °C using HadCM3), shows consistently greater discharge (maximum: 28.7%) in the upper catchment as global temperature increases, primarily due to increasing precipitation. Downstream discharge is strongly influenced by increasing PET, which outweighs increased upstream precipitation and results in consistent discharge reductions at higher temperatures (maximum: -5.3%). The magnitude of uncertainty associated with hydrological models is smaller than that associated with choice of GCM, with model differences attributed to alternative model structures, process representations, and methods for PET estimation.

Lauri et al. (2012) provide the most sophisticated assessment of climate change impacts on MRB runoff to date, contrasting the results of ten model runs based on five different downscaled RCMs using two different emissions scenarios (A1b and B1) (Table 4). As with Kingston et al. (2011), they show that there are significant uncertainties in the direction and magnitude of changes in runoff and river discharge, and that the variation in simulated discharge between individual climate models is relatively large. Modeled runoff for the entire MRB is shown to increase in six model runs (three for A1b and three for B1) and decrease in four runs (two for A1b and two for B1), with an overall range of -13.9 to +9.7%. The spatial pattern of runoff change in the lower part of the catchment is fairly similar for all the model runs, but varies in the middle and upper part of the catchment. In the lower part there is a decrease in runoff in the west, and varying amounts of increase in runoff in the east.

Under emission scenario A1b, in the middle part of the catchment three model runs show increasing runoff while two model runs show decreasing runoff (Figure 8). Also, in the uppermost part of the catchment the model runs disagree on the direction of change.

Projected change in annual discharge ranges from a 15.5% decrease to an 11% increase for the UMB at Chiang Saen, and a 10.6% decrease to 13.4% increase at Kratie. Wet season discharge at Kratie shows more variation between the different runs than the dry season discharges (except for December)---with a consistent increase for two runs, a varying decrease or increase for two runs, and a consistent decrease for one run. The end of the wet season/beginning of the dry season in September, October, and November as the most pronounced increase in discharge.

In the runs using the B1 emission scenario, the increase at Kratie in September–October compared to baseline is smaller than in the runs using the A1b scenario (Figure 8). There is also a decrease in monthly average discharge during June and July, which is not present in the A1b scenario runs. At Chiang Saen, the average monthly discharge decreases throughout almost the entire year in most of the runs using the B1 scenario, staying at the baseline level only during May and June. The largest decrease takes place in August (Lauri et al. 2012).

Table 4. Variation in estimates for the impact of climate change on average annual precipitation, maximum and minimum temperature, basin runoff, and annual discharge at Kratie and Chaign Saen, for five downscaled GCMs using the A1b and B1 scenarios. Scenario years 2032-2042 are compared to baseline 1982-1992. Note that discharge projections differ significantly with respect to direction as well as magnitude for different GCMs and scenarios (Lauri et al. 2012).

Model run	Prec. (%)	T_{max} (^oC)	T_{min} (^oC)	Runoff (%)	Discharge Kratie (%)	Discharge C. Saen (%)
A1b scenario						
CCCMA-CGCM3.1	7.8	1.09	0.72	9.7	13.4	4.9
CNRM-CM3	-2.5	1.2	0.80	-13.9	-10.6	-15.5
GISS-AOM	5.2	1.65	1.10	-3.5	-0.9	-5.1
MPI-ECHAM5	5.6	0.93	0.62	2.5	7.1	6.7
NCAR-CCSM3	8.6	1.41	0.96	6.9	10.9	110
B1 scenario						
CCCMA-CGCM3.1	5.8	0.86	0.59	5.7	8.1	1.2
CNRM-CM3	1.2	0.85	0.57	-3.5	0.1	-11.8
GISS-AOM	1.4	1.58	1.04	-10.2	-6.9	-6.3
MPI-ECHAM5	3.7	0.68	0.44	1.7	2.0	-4.4
NCAR-CCSM3	4.7	1.05	0.72	1.0	4.2	-5.7

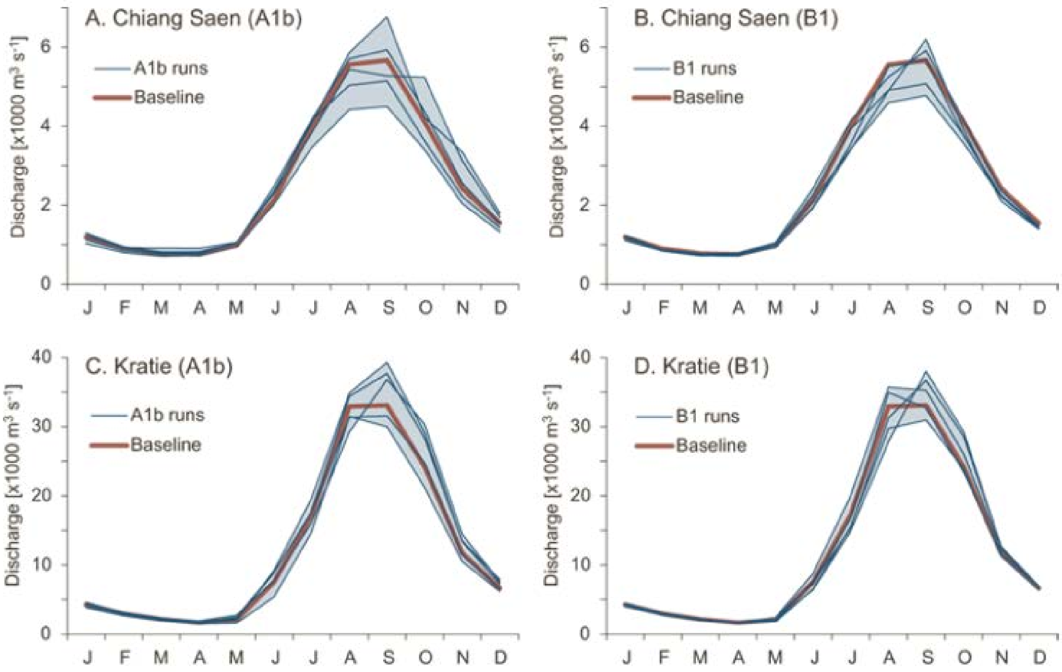

Figure 8. Impact of climate change on Mekong river discharge. Monthly average discharges of the models runs under A1b and B1 emission scenarios (2032-2042) compared to baseline (1982-1992) for Chiang Sean and Kratie. Note that discharge projections range from substantial increases to substantial increases relative to baseline, depending on the RCMs and scenarios selected (Lauri et al. 2012).

In summary, climate change models suggest that there is significant uncertainty in the magnitude and direction of change for annual and seasonal flows in the MRB, due in large part to uncertainties in model parameters and assumptions about future development scenarios. The majority of studies agree that flow is likely to increase at the beginning (May – June) and end (September – October) of the monsoon season. Projected changes in dry-season discharge vary among studies, with projections ranging from a slight increase to a substantial decrease during the dry-season months. Overall inter-annual variability in MRB flows is likely to increase, and there is a strong spatial variation in runoff projections across the physiographic regions of the MRB. This lack of clarity in the magnitude, variability, and seasonality of flow changes has profound implications for the assessment of climate change impacts on hydropower development, and for the adaptive management of hydropower infrastructure with greater uncertainty and variability in the future, as discussed below.

3 IMPACT OF CLIMATE CHANGE ON MEKONG RIVER BASIN HYDROPOWER

The potential impact of climate change on water resources has been a subject of global concern for decades (e.g., Arnell 1996; Arnell 1999). Changes in the quantity and timing of river runoff, together with increased reservoir evaporation, will have a number of effects on the production of hydroelectric power and IPCC scientists predict with very high confidence that climate change will affect the function and operation of existing water infrastructure and water management practices (Kundzewicz et al. 2007). In the past, feasibility studies have relied on historical rainfall and river flow data for the assessment of hydroelectric potential at a proposed site. However, in a changing climate these data may be no longer reliable for predicting future hydrological conditions and hydropower potential (Milly et al. 2008). Of particular concern is the impact of climate change on system operation, on the financial viability of hydropower projects (based on total energy production and firm energy contracts), and on the longevity and safety of hydropower dams (Harrison et al. 2000).

In this chapter, we review the existing and planned hydropower development in the MRB. We assess the impacts of climate change on hydropower development in the MRB, based on the possible changes associated with climate change assessed in the previous chapter. We identify gaps in knowledge about the impact of climate change on MRB hydrology and hydropower, and the applicability of knowledge and experience gained from other regions to the MRB.

3.1 Existing and planned hydropower infrastructure

In the UMB, the large elevation drop of the Lancang River (80% of the total Mekong decline) offers significant potential for hydropower generation, and many dams are in operation, construction, or planning on the mainstem Mekong (Figure 3A). The first phase of the Lancang River development consists of a seven dam cascade in Yunnan Province, China. The seven dams have a total generation potential of 15,450 MW, and include, from upstream to downstream, Gonguoqiao (completed in 2012; 750 MW), Xiaowan (completed in 2010; 4200 MW), Manwan (completed in 2007; 1550 MW), Dachaoshan (completed in 2003; 1350 MW), Nuozhadu (completed in 2012; 5850 MW), Jinghong (completed in 2009; 1750 MW), and Ganlanba (in planning; 155 MW) (Figure 9). An eight dam (Mengsong) was originally planned for the cascade, but has been cancelled. Two of the dams have very large reservoir live storage capacity, Xiaowan (9,895 Mm^3) and Nuozhadu (11,340 Mm^3) (MRC 2009b), that will significantly regulate the downstream Mekong flow regime (MRC 2001). The other dams are configured as run-of-river with relatively small reservoirs (MRC 2009b). The full cascade will have a live storage capacity of more than 23.2 km^3, corresponding to 28% of the mean annual flow that enters the LMB from Yunnan (Rasanen et al. 2012).

A second cascade consisting of eight additional hydropower dams is under construction or in planning for upstream of Gongguogiao, including Gushul (2600 MW), Wunonglong (990 MW), Lidi (420 MW), Tuoba (1400 MW), Huangdeng (1900 MW), Dahuaqiao (900 MW), and Miaowei (1400 MW) (HydroChina 2010; Grumbine and Xu 2011; www.internationalrivers.org). As many as 14 additional hydropower dams are planned for the Tibetan Plateau. If fully realized, the total installed capacity of the UMB would be greater than the massive Three Gorges Dam project on the Yangtze River, and 13 times greater than the total capacity of the Tennessee Valley Authority system in the United States (Hori 2000). Cumulatively, the dams would regulate more than 30% of Mekong mean annual flows from the UMB, significantly increasing dry season flows and reducing wet season flows. Substantial changes in downstream flow volumes and seasonal patterns are anticipated as far downstream as Kratie, where unregulated UMB runoff contributes as much as 40% of dry-season flows and 15% of wet season flows (MRC 2009b).

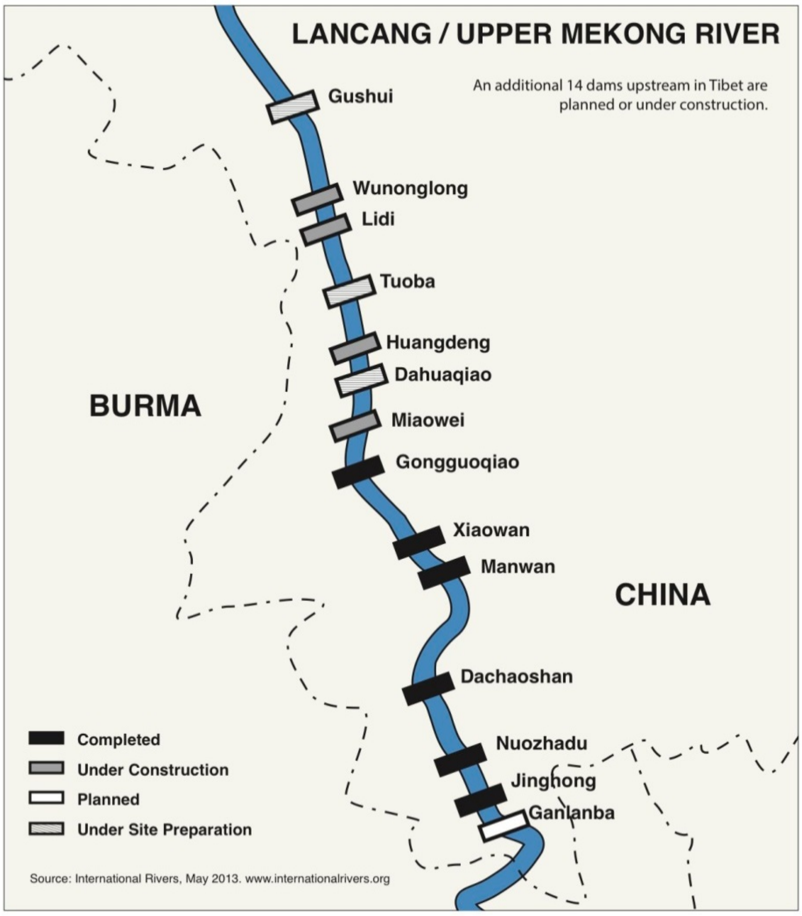

Figure 9. Large hydropower dams existing, under construction, planned, or in preparation on the Upper Mekong (Lancang) River in China (www.internationalrivers.org).

In the LMB, one mainstem dam is under construction, and an additional 11 mainstream projects are proposed – eight in Laos, two on the Lao-Thai border, and two in Cambodia, with a total installed capacity of 13,000 MW (MRC 2009b) (Figure 10). The total capacity of tributary dams, including those in operation, under-construction, and proposed, is nearly 29,000 MW, bringing the total capacity of hydropower generation in the LMB to nearly 42,000 MW from more than 130 hydropower projects (MRC 2009b).

The first six LMB dams are proposed above Vientiane, with the upper 5 dams connected in a cascade such that the tail waters of each dam flows directly into the headwaters of the next dam, creating a linked stepped reservoir of nearly 800 km (ICEM 2010). The five dam cascade is located in Laos, while the lowest dam, Pak Chom, is shared by Laos and Thailand.

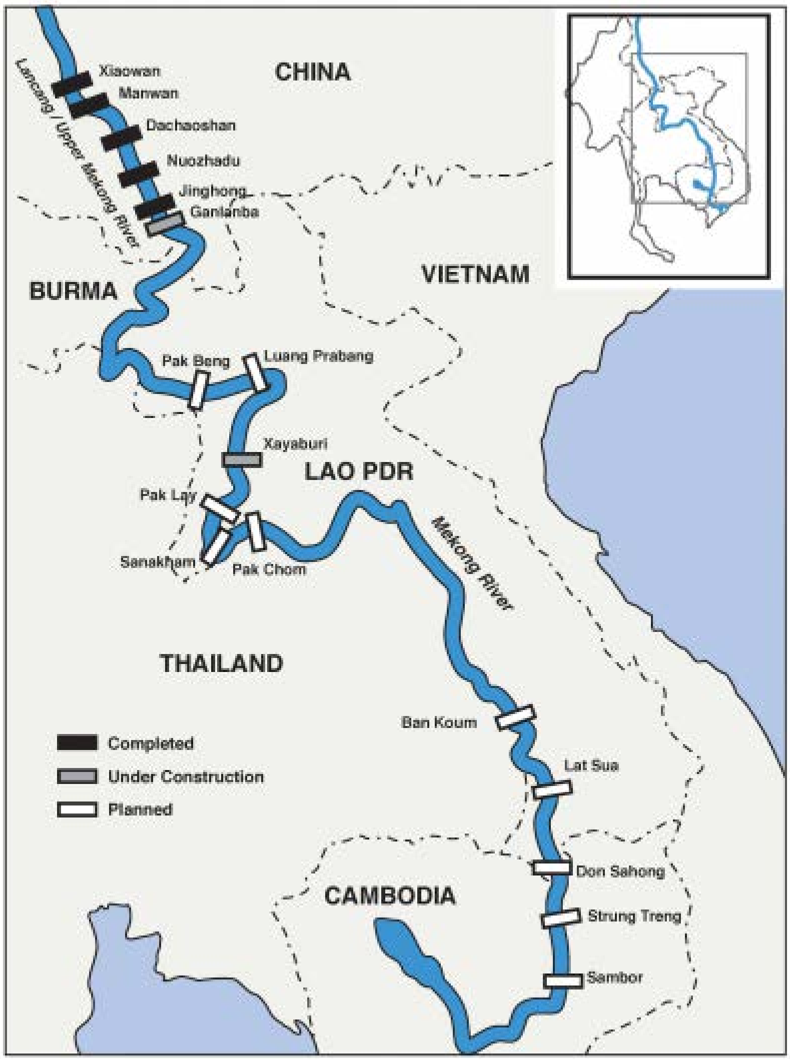

Figure 10. Large hydropower dams existing, under construction, or in planning on the mainstem Mekong River, including the lower cascade of the UMB and all proposed mainstem dams in the LMB (www.internationalrivers.org).

Pak Beng, the northern most of the LMB dams, would be located upstream of the town of Pak Beng, in Laos, with an installed capacity of 1,230 MW. The proposed dam is 943 m long, 76 m high, and has a rated head of 31 m. The proposed reservoir area is 87 km^2 with a live storage capacity of 442 Mm^3; 80% of the reservoir area is confined to the main channel (ICEM 2010).

Luang Prabang, the second dam in the cascade, would be located above Luang Prabang town, about 3 km above the confluence with the Nam Ou, with an an installed capacity of 1,410 MW. The proposed dam is 1,106 m long and 68 m high with a rated head of 40 m. It has a reservoir surface area of 90 km^2**,** 40% of which is contained within the channel, and a live storage of 734 Mm^3 (ICEM 2010).

Xayaburi, the third dam in the cascade, is the first one in the series of LMB dams currently under construction (MRC 2011b). The dam is located about 150 km downstream of Luang Prabang town, and will have an installed capacity of 1,285 MW. The dam is 810 m long and

32 m high with a rated head of 24 m. The reservoir surface area is 49 km^2 (96% confined within the main channel) and a live storage of 225 Mm^3 (ICEM 2010).

Pak Lay, the fourth dam in the cascade, would be located just above the district town of Pak Lay in Laos, with an installed capacity of 1,320 MW. The proposed dam is 630 m long and 35 m high with a rated head of 26 m. The reservoir would inundate a more substantial area (108 km^2) than the upstream dams in the cascade, with a live storage of 384 Mm^3 (ICEM 2010).

Sanakham, the final dam of the cascade to be located fully in Laos, would be situated just upstream of the Thai-Lao border, between Loei and Vientiane provinces, with an installed capacity of 700 MW. The proposed dam is 1,144 m long and 38 m high with a rated head of 25 m. The reservoir area is 81 km^2 (83% confined within the main channel), with a live storage of 106 Mm^3 (ICEM 2010).

Pak Chom, the first of the two dams shared between Thailand and Laos, would be located about 100 km upstream of Vientiane. It is not officially part of the upstream cascade, though its reservoir would extend back towards Sanakham (86 km upstream). The proposed project has an installed capacity of 1,079 MW with a dam 1,200 m long and 55 m high and a rated head of 22 m. The reservoir area is 74 km^2 (92% confined within the main channel) with live storage of 12 Mm^3. Pak Chom has 11 associated pumped irrigation schemes for a total of 2,700 ha in both Thailand and Laos (ICEM 2010).

The next two LMB dams are proposed between Vientiane and just downstream of Pakse, above and below the confluence with the Mun/Chi River.

Ban Koum, the second of the two dams shared between Thailand and Laos, would be located about 10 km above the confluence of the Mun/Chi River with the Mekong, with an installed capacity of 1,872 MW. The proposed dam is 780 m long and 53 m high with a rated head of 19 m. It has a reservoir area of 133 km^2 (86% confined within the main channel) and minimum live storage. Ban Koum has 22 associated pumped irrigation schemes for a total of 7,870 ha in both Thailand and Laos (ICEM 2010).

Phou Ngoy (previously called the Lat Sua), located 10 km downstream of Pakse, would have an installed capacity of 686 MW. The proposed dam is 1,300 m long and 27 m high with a rated head of 10.6 m. It has a small reservoir area of 13 km^2 (80% confined within the main channel) and very little live storage. Lat Sua has plans for associated pumped irrigation schemes for a total of 7,300 ha in Laos (ICEM 2010).

Two mutually-exclusive alternatives exist for hydropower development in the Siphandone area of Laos, Don Sahong or Thakho, neither of which would be full mainstream dams (ICEM 2010).

Don Sahong dam would block the Hou Sahong channel, one of more than ten channels that flow over the Khone falls at the southern end of Siphandone. The Hou Sahong channel is the only channel through the Khone Falls complex which enables fish passage during the dry season. The project takes advantage of the 15 – 18m drop at these falls and attracts a significant proportion of the flow into the small reservoir which forms in the channel. The proposed project has an installed capacity of 240 MW. The dam would be 720 m long and 8.2 m high with a rated head of 17 m. The reservoir is small (290 ha) with a live storage capacity of 115 Mm^3.

Thakho would involve a water diversion rather than a mainstem dam. About 380 m^3/sec of Mekong flow is diverted from above the Khone-Phapheng Falls, transferred through a 1.8 km channel constructed east of the Falls, and discharged through a power house about 1.5 km below the Khone Falls. The project has an installed capacity of 50 MW.

The two dams proposed in Cambodia, at Stung Treng and Sambor, would be longer than the other dams because they have to cross a wider floodplain, with larger reservoirs.

Stung Treng would be the uppermost of the two Cambodian dams, located about 10 km upstream of Stung Treng town and the confluence with the Sekong/Sesan/Sre Pok Rivers. It would have an installed capacity of 980 MW with an 11 km long and 22 m high dam, and a rated head of 15 m. The reservoir would extend up to the Cambodia/Lao border covering 211 km^2 with an active storage of 70 Mm^3 (ICEM 2010).

Sambor, the lowest dam of the LMB mainstream dams and largest in Cambodia, would be located near the village of Sambor, upstream of Kratie, and would inundate the river channel to just south of Stung Treng town. It would have an installed capacity of 2,600 MW, and a dam over 18 km long and 56 m high, with a rated head of 33 m. The dam would create a reservoir of 620 km^2 with an active storage of 465 Mm^3. (ICEM 2010). The developer is considering a smaller version of the project in which only half of the mainstream would be blocked.

The hydropower potential of LMB tributaries is very large, and more than 130 hydropower projects are either operating or projected (MRC 2011). Although Mekong mainstream dams have received considerable attention in the media and scientific literature (Hirsch 2010; ICEM 2010), tributary dam development is proceeding at a rapid rate and detailed studies on these developments are sparse (Pinman et al. 2012).

Nam Theun 2 (1,070 MW), the largest project in Laos, already accounts for 12% of the active storage capacity in the Mekong Basin (ADB 2004). Further hydropower development, consisting of individual dams and cascade dams, is rapidly progressing in the transboundary Sesan, Srepok, and Sekong (3S) river basin of Laos PDR, Vietnam, and Cambodia. The 3S basin drains 78,650 km^2 and contributes approximately 17 to 20% of total annual flows of the Mekong mainstream, an average of 2,886 m^3/s, making it the largest tributary contribution to the Mekong Basin and therefore of significant importance (Pinman et al. 2012; Adamson et al. 2009). The total potential for hydropower in the 3S basin is about 6,400 MW (MRC 2009b), and 42 dams are proposed. There are currently nine operating dams and 11 projects under construction with a total installed capacity of 3,643 MW and a total live storage of 6,196 Mm^3. Twenty one other projects are at various levels of planning stages (Pinman et al. 2012). Figure 11 shows the MRB tributary dams that are considered to have the highest likelihood of hydropower development under a very intensive development scenario (MRC 2009b).

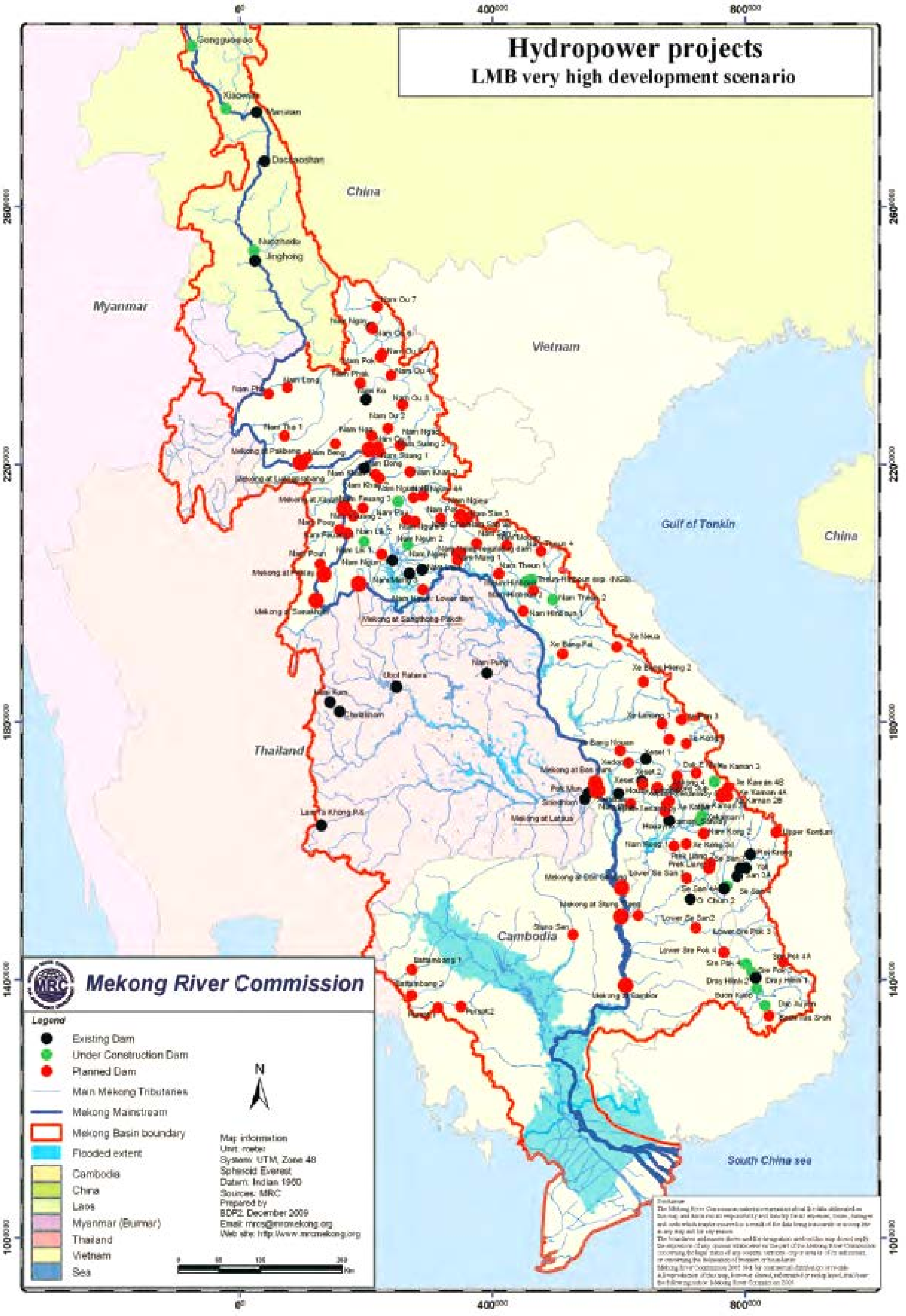

Figure 11. Large hydropower dams existing, under construction, or in planning in the LMB under the very high development scenario (MRC 2011a).

3.2 Impacts of climate change on existing and potential hydropower generation

According to the World Commission on Dams (WCD 2000), climate change has the potential to affect global hydropower installations in at least five important ways:

1. Changes in reservoir inflows on a seasonal and annual basis, due to increases or decreases in basin runoff and altered frequency and duration of drought conditions, affecting energy generation capacity;
2. Increased surface water evaporation, especially from upstream reservoirs and floodplains, reducing energy generation capacity;
3. Altered timing of the wet season flows, especially delayed onset of the rainy season, affecting dam operations as well as downstream release patterns;
4. Increased extreme flooding (inflow) events, due to higher rainfall intensity and more frequent and intense tropical cyclones, affecting dam safety and operational rule curves designed to prevent over-topping;
5. Increased sediment load to reservoirs, resulting from higher rainfall intensity and corresponding erosion, resulting in reduced reservoir capacity (lifespan) and water quality.

Furthermore, different hydropower schemes respond differently in their sensitivity and ability to adapt to changes in hydrological conditions associated with climate change (Blackshear et al. 2011). The type of hydropower facility (reservoir, run-of-river, or pumped storage), reservoir size, and reservoir surface area to volume ratio all have a significant influence on the impact of climate change on hydropower production. For example, run-of-river hydropower plants may be particularly vulnerable to reduced inflows and large reservoirs may result in substantial evaporative water loss as a proportion of inflows.

In the following section, we review the climate change factors affecting hydropower generation in the MRB, with specific reference to the existing and proposed hydropower infrastructure in the basin. Although quantitative modeling studies have not been undertaken, research on the impact of climate change on MRB hydrology (Chapter 2) and the existing and planned infrastructure for hydropower production in the basin (this chapter) provide considerable insight about future climate change impacts on MRB hydropower production.

Reservoir inflows

Long-term shifts in mean annual river discharge have a profound effect on energy generation capacity. The Mekong River Basin Strategic Environmental Assessment (ICEM 2010) assumes that increased Mekong discharge associated with climate change will improve hydroelectricity potential in both the tributaries and mainstream. The most recent modeling studies (notably Kingston et al. 2011 and Lauri et al. 2012) do not support this conclusion, however – the magnitude and direction (increase or decrease) of change in MRB discharge is unclear, and highly dependent on model parameters and assumptions about future emissions (as discussed in Chapter 2).

The impact on hydropower production of future changes in MRB discharge will depend on the design and operation of basin infrastructure. The “run-of-river” cascade of dams on the mainstem Mekong would experience a direct reduction in hydropower production in response to reduced dry season discharge, for example, due to a lower operating head.

These facilities would not have the capacity to increase hydropower generation when inflows exceed design specifications, however – "excess" inflows would be spilled without added energy production. The 26.5% range in potential discharge values at Chiang Saen relative to baseline modeled by Lauri et al. (2012) underscore the vulnerability of hydropower production in the LMB cascade to changes in inflows.

Large reservoir systems (e.g., Xiaowan and Nuozhadu in the China, Nam Theun 2 and other large tributary dams in Laos, and, to a lesser extent, Stung Treng and Sambor in Cambodia) with the capacity to store inflows over multi-year cycles would provide some buffering against increasing variability of annual inflows. A long-term increasing trend in Mekong inflows to large reservoirs may improve hydropower generation relative to design specifications, whereas a long-term reduction in reservoir inflows may directly reduce hydropower production depending on reservoir capacity relative to inflows.

The projected increase in the frequency and magnitude of droughts in the MRB (Chapter 2) is a more clear threat to hydroelectric generation, directly reducing the amount of water available (river discharge, reservoir storage volume) to produce electricity (Deinhard 2012). All types of hydroelectric facilities are affected by reduced dry season inflows associated with droughts, although run-of-river facilities are particularly vulnerable. The impact on power production in the MRB will depend on the magnitude of change in the frequency and duration of drought events over time. Firm power contracts for electricity sales from hydropower plants typically assume that production targets will be met 95-98% of the time. Power shortfalls due to recurrent drought would significantly undermine such contractual obligations. In recent years low inflows at the end of rainy season, when reservoirs maintain substantial excess storage capacity to capture expected additional (heavy) rainfall, resulted in a significant reduction in hydropower in the dry season of subsequent year (C.T. Hoanh *pers comm*). In Cambodia, several existing dams are only able to operate at 10% or less of their design capacity during the dry season, significantly lower than the levels predicted by feasibility studies and Environmental Impact Assessments. This reduction has major implications for overall energy production, as dry season energy demand is highest in the region. Cambodia's Prime Minister suggested that Cambodia will need to build coal-fired plants to off-set the lack of energy being produced by hydropower (Grimsditch 2012).

The increased rate of glacial melting is expected to have a minor impact on hydropower production, with a slight increase in UMB discharge in the short-term as water resources stored in glaciers are released, and a nominal decrease in UMB discharge in the long-term as glaciers disappear (Deinhard 2012). The shift in UMB winter precipitation from predominately snow to rain would lead to a temporal shift in peak flow and winter flow conditions (Stickler and Alfredsen 2009). The spring snowmelt peak would shift earlier or be eliminated entirely, with winter flow increasing.

Altered baseflows (groundwater inflows), resulting from changes in groundwater recharge associated with changes in precipitation and evaporation, would also affect hydropower generation. The direction and magnitude of change in groundwater availability relative to current baseline is unclear, however, and requires further study (Chapter 2).

Reservoir evaporation

Increased evaporative water loss is directly associated with climate change, reducing the volume and elevation of water available for electricity generation in all types of dams. The LMB run-of-river schemes with relatively high surface area to volume ratios may be vulnerable to reduced generation capacity due to evaporative water loss, with smaller reservoirs more at risk to losing a greater proportion of their volume to evaporation –

however, the overall magnitude of water loss relative to inflows may be minor (McJannet et al. 2008, Rydgren et al. 2007). Large deep reservoirs, such as Xiaowan and Nuozhadu on the mainstem, or Nam Theun 2 on the tributaries, are less vulnerable but can lose large volumes of water associated with higher rates of evaporation, reducing reservoir storage volume and water availability downstream for power production or ecosystem services. As noted in Chapter 2, the magnitude of increase in evaporation associated with climate change relative to current baseline is uncertain and critically important. A modest 2% increase in evaporative water loss from just the Nam Theun 2 reservoir, for example, would result in an annual 13.5 Mm^3 water loss from the LMB, and the cumulative evaporative water loss of all existing and proposed reservoirs would fundamentally alter water availability in the MRB. Given that annual variation in MRB flows is much higher than this volume, hydropower operators may not consider this system water loss as important to overall power production.

Altered timing of reservoir inflows

Seasonality of precipitation and runoff causes variability in hydroelectric generation, and regions with distinct seasonal rain cycles and snowmelt seasons typically experience fluctuations in generation related to seasonal variations in river discharge (Blackshear et al. 2011). Increases in temporal variability (due to a delayed onset of the monsoon, or an extended duration of the dry season due to early cessation of monsoon rains) will reduce the potential for hydropower production, especially in the subsequent dry season, with different hydropower facilities responding differently depending on configuration. Hydropower production in LMB run-of-river dams that are directly dependent on river flows is expected to be more significantly affected by varied and less unpredictable inflows than larger reservoir dams which may be able to compensate for decreased flow through adaptive reservoir management (Blackshear et al. 2011). Power production in run-of-river schemes may be unaffected during high flow seasons, spilling excess waters, but may experience sharp decreases in low-flow months. As climate change impacts intensify, this variation will be exacerbated, making it more difficult for hydropower facilities along the Mekong River to predict river discharge and to generate an even supply of power (Deinhard 2012).

Extreme flooding events

The effects of climate change on hydropower dams are not limited to production patterns; extreme flood volumes may exceed dam design limitations, over-topping dam walls and increasing the risk of structural failure, or delivering sediment and debris that block dam spillways and damage important structural components (Hauenstein 2005). Eastham et al. (2008) recommend that future MRB dam design take into account changing probabilities of rainfall and runoff events of different magnitudes to ensure structural stability.

ICEM (2010) notes that the hydropower sector will also face an increasingly complex and severe risk profile. The projected increase in extreme wet events and incidence of flood events brings a risk of catastrophic failure. Climate change may turn a 1 in 10,000 year flood risk into a more frequent event – for example to a 1 in 1,000 flood (Table 5). A component designed for a *1 in 1,000 year* event would see the probability of this event occurring over the design life increase from 10% to 63%, and each of the MRB dams is almost certain to experience a (baseline) 1 in 100 year event with climate change. If not fully accounted for in dam designs and safety measures, including retrofitting, the increased likelihood of extreme events will increase the risk of dam break and failure of key hydraulic components (e.g. spill way gates).

Table 5. Comparison of changes to the magnitude of extreme events for the same return period over an estimated project life of 100 years: 1 in 10,000 year events would become 1 in 1,000 year events with climate change (ICEM 2010).

	EXTREME VALUE DISTRIBUTION				**EXTREME VALUE DISTRIBUTION**			
	Historic return period flow				Projected return period flow in 2030 with climate change			
Station	10yr	100yr	1,000	10,000	10yr	100yr	1,000yr	10,000
Chiang Saen	12,252	14,551	16,808	19,091	13,209	15,769	18,282	20,790
Luang Prabang	17,137	19,912	22,637	25,357	18,783	22,362	25,876,	29,384
Vientiane	18,670	21,285	23,852	26,414	19,692	22,745	25,742	28,734
Pakse	40,842	45,344	49,765	54,177	43,459	49,149	54,734	60,311
Kratie	56,254	62,934	69,493	76,040	59,000	66,886	74,629	82,358

Accelerated melting of glaciers also is predicted to result in flooding and landslides that could threaten dam safety in the UMB (WWF 2005). Glacial lake outburst floods (GLOFs) are catastrophic discharges of water resulting from melting glaciers. Retreating glaciers can produce large glacial melt water lakes. The moraine dams impounding these lakes are structurally weak and unstable, undergoing constant changes due to slope failures and slumping, and may break due to external triggers or self-destruction. The sudden release of huge amounts of lake water, mixed with moraine materials, creates dangerous flood waves in the downstream channel and cause devastation for downstream riparian communities as well as hydropower stations and other infrastructure. In the South Asian Himalayan region, the frequency of occurrence of GLOF events increased during the second half of the 20th century (WWF 2005).

Dams management practices may exacerbate flooding during extreme events as well. In the Sesan River tributary, extreme floods and tropical storms have forced dams to release water to prevent over-topping, resulting in highly destructive downstream floods and water surges, including many deaths. Following Typhon Ketsana, the government of Vietnam reconsidered many of the proposed dams in the Central Highlands due to unacceptable levels of flood risk. Managers of smaller hydropower reservoirs, concerned with dam safety, often are unwilling to operate the reservoirs close to design capacity (www.internationalrivers.org).

Overall, the magnitude of flows associated with extreme flooding events in the MRB is enormous and dam failure during an extreme event could have catastrophic consequences for downstream communities. Many of the important cities of the Mekong could be at risk in the case of failure, including Vientiane, Pakse, Luang Prabang, Pak Lay, Stung Treng, Kratie, and Kampong Cham (ICEM 2010). Adaptation procedures and risk management practices that incorporate projected hydrological changes with related uncertainties are essential to future development and management of MRB hydropower systems.

Reservoir sedimentation

Climate change may also affect reservoir lifetime through increased sediment transport due to erosion, and reservoir deposition. Changes in rainfall intensity may impact reservoir life and stability, through greater rates of erosion and reservoir sedimentation (Bates et al. 2008). A shift in winter precipitation from less erosive snow to more erosive rainfall due to increasing winter temperatures would also contribute to increased erosion and sedimentation. As discussed further in Chapter 5, changes in erosion and sediment transport associated with climate change and river basin development are of major concern in the MRB. Darby et al. (2013) assessed how the monsoon, tropical storms, and snowmelt affect Mekong bank erosion, and several studies have investigated sedimentation in the mainstream hydropower dams (Kummu & Varis 2007, Walling 2010, Kummu et al. 2010, Xue et al. 2011, Wang et al. 2011). The UMB Lancang cascade reservoirs have the theoretical capacity to trap 94% of suspended sediments (Kummu and Varis 2007; Kummu et al. 2010). According to MRC (2011a) LMB reservoirs could effectively lose about 60% of capacity due to sedimentation after 30 years under proposed operating conditions, compromising power generation in the medium to long term. Finally, it should be noted that adaptation responses to climate change impacts could result in improved land use practices that meaningfully reduce rates of erosion and sediment transport in the MRB.

3.3 Gaps in knowledge and lessons learned from global studies of impact of climate change on hydropower production

Our review of available knowledge of climate change impacts on MRB hydrology and hydropower development revealed considerable gaps in knowledge that have profound implications for water resources development in the region. Uncertainty about future hydrology presents a great challenge for infrastructure planning and engineering (Beilfuss 2012). Most hydropower projects are designed on the basis of recent climate history (typically a 30-50 year historic time series of flow data) and the assumption that future hydrological patterns (average annual flows and their variability) will follow historic patterns. This notion that hydrological patterns will remain “stationary” (unchanged) in the future, however, is no longer valid (Milly *et al.* 2008). Under future climate scenarios, a hydropower station designed and operated based on the past century’s record of flows is unlikely to deliver the expected services over its lifetime. It may be over-designed relative to expected future water balances and droughts, as well as under-designed relative to the probability of extreme inflow events in the future. Water resource developers and managers, therefore, are dependent on accurate hydrological models that incorporate future climate projections from climate models.

Although numerous modeling studies have projected changes in Mekong River discharge associated with climate change, as discussed above, model results are inconsistent and no models have been developed to quantify the impact of climate change on MRB hydropower development, even at the course spatial and temporal scales applied in other studies (e.g., Harrison et al. 2003, Harrison et al. 2006, Beilfuss 2010). The development of appropriate models is plagued by uncertainties associated with the GHG emissions scenarios selected, the GCMs used, the statistical and dynamical downscaling to RCMs, the methods for transferring the climate change signal to hydrological models, and the hydrological models developed. The need for multi-model evaluations is particularly important, both for climate models (e.g., Kingston et al. 2011, Lauri et al. 2012) and hydrological models (Johnston and Kummu 2012; Thompson et al. 2013). Addition uncertainties result from the paucity of field observations required to calibrate and verify models (e.g., Rydgren et al. 2007). Bates et al. (2008) note that better observational data and data access are essential to improve understanding of ongoing changes, to better constrain model projections, and are a prerequisite for adaptive management required under conditions of climate change.

Lessons learned from studies of climate change impacts on hydrology and hydropower development in other river basins may help fill some of the knowledge gaps for the MRB. Rydgren et al. (2007) reviewed the global literature on the context of hydrological variability and the impact of climate change on hydropower/reservoir operation, combined with personal contacts with researchers and operators in the field, and revealed that very little quantitative work has been done. IPCC scientists (Kundzewicz et al. 2007 and Bates et al. 2008) found examples of both positive and negative regional effects on hydropower production, mainly related to expected changes in river runoff. Few quantitative studies are available, and most were conducted in Europe and North America, with a relatively weak literature base for sub-tropical and tropical regions. Nonetheless, some findings are highly relevant to the MRB context, and are summarized below.

In other major hydropower-generating regions of Asia, including China, India, Iran, and Tajikistan, projected changes in runoff are predicted to have a significant effect on the hydropower production (Rydgren et al. 2007). Increased risks of landslides and glacial lake outbursts, and impacts of increased variability, are of particular concern to Himalayan countries (Agrawala et al. 2003). Iimi (2007) proposed increasing reservoir storage capacities to accommodate increased intensity of seasonal precipitation. In the Indus River Basin, hydropower assessment is confounded by difficulties in simulating the impact of monsoonal seasonality on the precipitation in the highest and most glaciated parts of the Himalaya (Harrison and Whittington 2001). Several scenarios predict increased precipitation and hydropower production in the Indus River, but others suggest a reduction in output (Reibsame et al. 1995).

In Australia, modeling studies by Hydro Tasmania found that despite a projected increase in future rainfall, a concomitant reduction in hydropower production is projected due to increasing variability. They noted that existing run-of-river stations lack sufficient storage capacity to capture increased winter flows for release in the spring, resulting in increased winter spillage and generation short-falls during spring-summer (Rydgren et al. 2007).

In Africa, climate is already a major factor in hydroelectric production. Recurring droughts have plagued hydroelectric dams, at times reducing plants to half of their capacity, and more frequent power shortages due to drought are projected for the future (Mukheibir 2007, Waylen 2008). Beilfuss (2012) notes that in the Zambezi River Basin under future climate scenarios, hydropower projects based on the historic record of flows are unlikely to deliver the expected services over their lifetime. Existing and proposed dams both are over-designed relative to expected future water balances and droughts, and under-designed relative to extreme inflow events.

In Europe, the EuroWasser study (Lehner et al. 2005) used the WaterGap model to assess and compare the impact of climate change on hydropower potential. Two different GCMs (ECHAM4 and HadCM3) were interpolated to a 50 km horizontal grid used for hydrological modeling, based on a 30-year time series. By the 2070s, the electricity production potential of hydropower plants in projected to increase by 15-30% in Scandinavia and northern Russia, and decrease by 20-50% in Portugal, Spain, Ukraine, Bulgaria, and Turkey. For the whole of Europe, hydropower potential shows a decrease of 7-12% by the 2070s.

Scandinavia and northern Russia are predicted to experience increased runoff, but this change does translate to a direct, equivalent increase in hydropower production (Rydgren et al. 2007). Depending on the timing of precipitation events and the resulting discharge, as well as the storage capacity of a dam, a site that is projected to experience greater discharge volume could actually see lowered power production potential because of more extreme high and low flows projected. Run-of-river dams are particularly susceptible to changes in flow pattern because of their inability to store discharge that exceeds maximum production capacity (Lehner et al. 2005). In Sweden, climate models predict increased precipitation in winter and increased fluctuations between dry and wet years (Hauenstein 2005). The effect of increased precipitation on runoff is countered in part by increased evaporation and evapotranspiration. Hydropower production from run-of-river plants at lower altitudes is projected to increase in winter and reduce in summer due to less rainfall and the lack of snow reserves.

Tuomenvirta et al. (2000) examined the impact of climate change on dam safety in Scandinavia. Risks for some dams increase with projected climate change, but remain similar to present conditions or decrease at others. Results from Finnish studies show that there are large increases in projected design floods associated with climate change for most dams in the country, and serious concerns for dam safety on 5-12 dams depending on the scenario used (Veijalainen and Vehviläinen 2006).

In North America, the expected long-term increase of annual and seasonal precipitation in parts of Canada has the capacity to increase hydroelectric output in those areas, but the overall benefits for hydropower production are mixed. One study in the Peribonka River watershed in Quebec, Canada predicted mean annual hydropower to decrease by 1.8 percent between 2010-2039 (due to initial early peak flows and lack of summer precipitation) and subsequently increase by 9.3 percent and 18.3 percent during 2040-2069 and 2070-2099 respectively (due to steadily increasing precipitation amounts) (Minville et al. 2009). The initial decrease in production, due to low summer flows, is expected to affect run-of-river dams more strongly than reservoir dams. Other concerns include the increased volatility of discharge due to more frequent extreme events and changing seasonal patterns, which is expected to lower the reliability of reservoirs to store water efficiently, and changes in peak flows, which are expected to occur earlier with reduced discharge.

Global changes in the frequency of extreme flooding events were examined by Milly et al. (2002). They projected that the 100-year peak volumes of monthly river flows in 15 out of 16 large basins worldwide will be exceeded more frequently under climate change. In some basins, the current 100-year flood event is projected to occur much more frequently, even every 2–5 years, albeit with a large uncertainty in these projections.

Only very limited work has been done on the expected impacts of climate change on sediment loads in rivers and streams, and their impact of hydropower reservoir capacity and lifespan. Bouraoui et al. (2004) showed, for southern Finland, that the observed increase in precipitation and temperature was responsible for a decrease in snow cover and increase in winter runoff, which resulted in an increase in modeled suspended sediment loading to reservoirs. Sedimentation of reservoirs in Northeastern Brazil is significantly decreasing water storage and water supply (De Araujo el al. 2006), and erosion resulting from increased precipitation intensities is expected to exacerbate this problem (Kundzewicz et al. 2007). The La Plata River drainage basin is likely to see significantly higher rates of sediment deposition in the coming decades associated with increased rainfall in the region, as well as increased river discharge (Soilto and Freitas 2011). Increased sedimentation will require costly river dredging operations on an annual basis to ensure sufficient flows for hydropower production (Rydgren et al. 2007).

Numerous studies indicate that hydropower economics are sensitive to changes in precipitation and runoff (Alavian *et al.* 2009; Gjermundsen and Jenssen 2001; Mimikou and Baltas 1997; Harrison and Whitington 2001; Harrison et al. 2003; Whittington & Gundry 1998; Pittock & Hartmann 2011). Harrison et al. (2000) note that reductions in electricity sales resulting from climate-driven changes in hydropower would affect the return on investment and hence the viability of hydropower projects. The loss of hydroelectric generating capacity will require additional plants to be constructed to meet demand, requiring additional capital and thus reducing overall system returns. Financial and technical analyses to assess the feasibility of hydropower projects typically evaluate the financial impacts of a range of factors on the ability to generate a positive cash flow; these analyses apply traditional engineering cost/financial analysis to characterize construction and operational costs (e.g., size and location of the project) and future trends that could affect project revenues (e.g., changing demand, new supply, and economic drivers affecting the price of electricity). These assessments rarely evaluate potential power generation and associated revenue changes associated with climate change, and there is no evidence of such studies associated with hydropower planning and development in the MRB.

When climate considerations are incorporated, the financial risks may significantly undermine the feasibility of existing and future hydropower projects (Beilfuss 2012). Certain hydropower schemes might be over-designed in relation to changes in future water balances and droughts, as well as under-designed in relation to the probability of extreme inflow events in the future. Over-designed projects, resulting from reduced and more variable inflows relative to the historical time series, incur financial risk by generating lower levels of power production than forecast, leading to reduced electricity sales and revenue, including failure to meet firm energy commitments (Beilfuss 2012). The occurrence of extreme flooding events on a more frequent basis (Boko *et al.* 2007) may threaten the stability of under-designed dams and/or force more frequent spillage, which exacerbates downstream flood damage.

Finally, Rydgren et al. (2007) noted that most hydropower/reservoir operators do not see climate change as a particularly serious threat. The existing hydrological variability is more of a concern, and the financially relevant planning horizons are short enough that with variability being much larger than predicted changes, these latter do not seem decisive for planning. Where studies focusing on the reservoir storage component of climate change have been implemented, the insecurities in modeling results are considerable. Different global climate models often contradict each other, although there is increasing agreement in the results from such models. Models also have difficulties with predicting the seasonal distribution of rainfall, a key determinant for operational adaptation in reservoir management for hydropower production. Hartmann (2008) adds that hydropower planners have been aware of climate change for years, but until recently it was assumed that climate trends were too uncertain, and the range of natural variability too high, to make reliable predictions. From a financial point of view, it was argued that changes beyond 20-30 years from present would have little impact on the financial return of hydropower investments – introducing a mismatch between financial time horizons and water resource management implications, as the physical lifespan of hydropower assets is much longer than the pay-back period.

In summary, it is widely acknowledged that climate change will lead to changes in the hydrological regime in many countries, including the MRB, with shifts in mean annual rainfall and increased variability, and more frequent hydrological extremes including floods and droughts (Rydgren et al. 2007). Increased evaporative water loss from hydropower reservoirs can have a significant impact on hydropower production. For regions such as the UMB where much winter precipitation falls as snow, global studies suggest that higher temperatures are expected to lead to changes in seasonality of river flows (Barnett et al. 2005). Observational evidence indicates that increased runoff and earlier spring peak flows are already occurring in many glacier and snow fed rivers. For warmer regions driven by rainfall, including the LMB, changes in precipitation will play a larger role than changes in temperature, and rain-dominated river basins tend to show increases in flow seasonality. Kumar et al. (2011) note that increased climate variability, even with no or slight increases in average runoff, can lead to reduced hydropower production unless more reservoir capacity is built and operations are modified to account for the changing hydrological conditions. Investors in MRB hydropower will be wise to carefully consider the implications of changing climate, especially the high level of variability and uncertainty, on the future development of the region.

4 ROLE OF MEKONG RIVER BASIN HYDROPOWER DEVELOPMENT IN MITIGATING CLIMATE CHANGE IMPACTS

Hydropower has been suggested as a global response to climate change challenges. Hydropower has the potential to contribute to global climate change mitigation due to its low levels of greenhouse gas (GHG) emissions relative to fossil fuel-based energy sources. Hydropower reservoirs also have the potential to provide water supply and manage floods and droughts, reducing the vulnerability of local populations to climate change impacts (World Commission on Dams 2000). This section examines the potential for hydropower development in the MRB to mitigate climate change impacts with respect to reducing global GHG emissions in energy production, and managing floods and droughts through reservoir management.

4.1 Hydropower and GHG emissions

On a global scale, 85% of primary energy consumption is sourced from non-renewable fossil fuels (coal, oil and gas) and traditional fuels (wood), with associated large-scale GHG emissions to the atmosphere: CO2 from combustion, and methane from processing coal and natural gas. Hydropower is increasingly promoted as a renewable source of energy with low GHG emissions, with production capacity at a scale necessary to meet pressing energy demands with current technology (Pittock 2010). Supporters argue that large-scale hydropower development will mitigate the impacts of climate change. The International Hydropower Association recommends that “the remaining hydro potential should be developed [for climate change mitigation] to the maximum possible extent, provided it is implemented in a technically, economically, environmentally, and socially acceptable way” (Hauenstein 2005).

These perspectives are bolstered by studies from temperate regions indicating that emissions from hydropower systems in boreal ecosystems are typically 30-60 times less than comparable levels of energy generation from fossil fuels (Gagnon 1999). Other studies have suggested that development of half of the world's economically feasible hydropower potential could reduce GHG emissions by about 13%, with significant reductions in sulphur dioxide (the main cause of acid rain) and nitrous oxide emissions as well (Oud 1999).

The Kyoto Protocol recognizes some hydropower dams as Clean Development Mechanisms (CDM). CDM allow a country with an emission-reduction of limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits, each equivalent to one ton of CO_2, which can be counted towards meeting Kyoto targets. Hydropower projects are one of the largest contributors to the CDM. In 2010, 562 out of 2062 registered CDM projects were hydropower projects (Kumar et al. 2011), including 117 CDM projects registered in the LMB countries (Laos and Vietnam) and others awaiting verification (Deinhard 2012). Globally, hydropower CDM projects were expected to generate more than 47 million tons of CO_2 emission reductions per year by the end of 2012, the end of the first commitment period of the Kyoto Protocol. This is equivalent to 14% of all registered CDM project reductions (336 million CERs) (Kumar et al. 2011).

Large hydropower reservoirs with significant water storage are excluded from CDM credits due to uncertainties about emissions from freshwater reservoirs, especially in the tropics, discussed below.

Kumar et al. (2011) provide a Life Cycle Assessment (LCA) for hydropower projects. An LCA compares the full range of environmental impacts assignable to products and services, across their lifecycle, including all processes upstream and downstream of operation or use of the product/service. The LCA for hydropower plants consists of three main stages:

- Construction: GHGs are emitted from the production and transportation of materials (e.g., concrete, steel etc.) and the use of civil work equipment and materials for construction of the facility (e.g., diesel engines).
- Operation and maintenance: GHG emissions can be generated by operation and maintenance activities, most notably emissions from rotting vegetation in reservoirs when landscapes are inundated, and from carbon inflows from the catchment. Also noted are building heating/cooling systems, auxiliary diesel generating units, or onsite staff transportation for maintenance activities.
- Dismantling: Dams can be decommissioned for economic, safety or environmental reasons. Up to now, only a small number of small-size dams have been removed, mainly in the USA. Therefore, emissions related to this stage have rarely been included in LCAs so far.

The majority of lifecycle GHG emission estimates for hydropower cluster between about 4 and 14 g CO_2eq/kWh, but under certain scenarios there is the potential for much larger quantities of GHG emissions (Kumar et al. 2011). A theoretical calculation for the Tucurui Dam in Brazil, using 'worst case' assumptions concerning the decomposition of flooded biomass (that 100 per cent of the biomass would decompose over 100 years, and that 20 per cent of biomass carbon would be emitted as methane), generated an emission factor of 213 g CO2eq/kWh. Conversely, a recent World Bank study suggests that globally GHG emissions from reservoirs have been greatly over-estimated in the past (Liden 2013).

Bates et al. (2008) notes that the magnitude of GHG emissions from hydropower dams depends on specific circumstance and mode of operation. Greenhouse gas emissions vary with reservoir location, power density (power capacity per area flooded), flow rate, and whether the plant is dam-based or run-of-river type. Recently, the greenhouse gas footprint of hydropower reservoirs has been questioned. Some reservoirs have been shown to absorb carbon dioxide at their surface, but most emit small amounts of GHGs as water conveys carbon in the natural carbon cycle. High emissions of methane have been recorded at shallow, plateau-type tropical reservoirs where the natural carbon cycle is most productive, while deep-water reservoirs exhibit lower emissions. Methane from natural floodplains and wetlands may be suppressed if they are inundated by a new reservoir, since methane is oxidised as it rises through the water column. Methane formation in freshwater involves by-product carbon compounds (phenolic and humic acids) that effectively sequester the carbon involved.

The MRB is highly dependent on electricity that produces high GHG emissions. About 90% of electricity generated in the LMB is generated from hydrocarbons (natural gas, coal, and petroleum products). The region as a whole imports about 22% of the energy used in electricity generation (oil, coal and gas) and fossil fuel imports for power generation are projected to rise. Significant fossil fuel development within the region includes lignite coal deposits under development in Laos, and off-shore oil reserves in Cambodia with as much as 2 billion barrels of oil and 10 trillion cubic feet of gas. Thailand exploits natural gas reserves in the Gulf of Thailand (Deinhard 2012).

In this context, the role of hydropower development in reducing GHG emissions appears attractive to many decision-makers seeking to meet large-scale energy demands. According to the MRC Basin Development Plan, hydropower contained in the 20-year Probable Future Scenario (PFS) would lead to a reduction of some 42 million tonnes of CO2 emissions per year by 2030, through displacement of fossil fuel generation in Thailand, Viet Nam and to a lesser extent in Cambodia (Deinhard 2012). If all LMB mainstream dams were to proceed, this amount would increase to 94 million tonnes CO2 emissions per year. The emissions of GHG from the reservoirs of all LMB hydropower schemes combined is estimated to be 13 million tonnes of CO2 tons of carbon, and needs to be subtracted (MRC 2011a).

ICEM (2010) analyzed emissions avoided by 2030 if 65,000 GWh of power is produced by the mainstream MRB dams, including estimates of reservoir emissions, and indicate that about 50 million tonnes CO_2/yr could be avoided by the mainstream dams. They note that reduction is equivalent to 15 million tonnes of coal-fired generation per annum. The need for further research to better understand future GHG emissions associated with climate change and river basin development is clearly needed, however. A recent study by Finnish researchers suggests that GHG emissions associated with the Lower Sesan 3 Dam and other projects in Laos and Cambodia will have similar emission levels as a coal fired plant, for example (Lee and Yan 2013).

Ultimately, the role of hydropower in reducing GHG emissions in the MRB must be weighed against other alternatives to fossil fuels for meeting energy demand. This is especially important because hydropower projects are associated with social and environmental changes that may aggravate, rather than mitigate, the impact of climate change (Chapter 5). Alternatives for reducing GHG emissions in the MRB include harnessing renewable resources, including biomass, solar, wind, geothermal resources, making energy efficiency improvements in buildings and industry, and using more efficient and cleaner transport (ADB 2009). Renewable energy sources offer some immediate and longer-term potential for the regional power grid and off-grid applications. Thailand aims to reach 20% (11,216MW) of its 2022 energy demand from renewable energy sources. This amounts to 78% of Thailand's medium-term renewable energy potential (14,300 MW), including biomass (7,000 MW), solar (5,000 MW), small hydropower (700 MW), and wind (1,600 MW). Both Viet Nam and Thailand favor nuclear power development - Viet Nam has plans for up to 8 nuclear reactors supplying 20% of grid supply by 2030 and Thailand aims to have 5-7 nuclear reactors within the same time horizon (ADB 2009). Cogeneration and other non-conventional energy resources are untapped resources (Deinhard 2012). Demand side management, especially in Thailand and Vietnam, is another alternative for reducing GHG reductions. By 2007, Demand Side Management initiatives in Thailand reduced peak demand by an estimated 1,435 MW and energy consumption by 8,148 GWh/yr. Viet Nam has reduced peak demand by an estimated 120 MW and energy consumption by 496 GWh/yr by 2007 (ICEM 2010).

Finally, Pittock (2010) stressed the importance of climate policy and institutions to optimize the use of hydropower for mitigation of climate change impacts and limit its negative impacts. Climate change policies are altering the application of most energy technologies. In the case of hydropower pumped storage schemes are taking a new role, and one that has great flexibility in providing economic benefits while limiting impacts compared to conventional hydropower. Large-scale energy systems are needed for energy management for the growth of other renewable energy sources such as wind and solar energy. Socially and environmentally, pumped storage hydropower projects have not been systematically assessed but are expected to have lesser impacts since projects can be constructed off-river and using existing storages; off-river pumped storages require very little land, and the water is largely recycled so consumption is low. Using existing dams for pumped storage may result in opportunities and funding for retrofitting devices and new operating rules that reduce previous ecological and social impacts (Deinhard 2012).

4.2 The role of hydropower in other climate change mitigation

Hydropower development is often credited with reducing climate change impacts at the river basin scale, through the management of extreme events (floods and droughts) that are likely to increase with climate change. Many hydropower projects are justified on the basis of providing flood control and water supply in addition to energy generation. In river systems such as the MRB with large seasonal and year-to-year variability in inflows, reservoirs store water (and energy) during periods of water surplus, and release water during periods of deficit, making it possible to produce a steady supply of energy while controlling flood pulses and buffering downstream areas from the impacts of floods and droughts. Most reservoirs are built for supplying seasonal storage, but some also have capacity for multi-year regulation, where water from two or more wet years can be stored and released during a later sequence of dry years.

Hydropower reservoirs potentially can have a significant role in helping MRB countries better adapt to climate change, mitigating against extreme floods and droughts and providing waters for water supply, irrigation, navigation, and other uses. Lacombe et al. (2013) suggest that existing and planned reservoirs in the Nam Ngum basin have the potential to greatly enhance opportunities for irrigation on the Vientiane Plain under climate change, for example. Adaptation requires pro-active measures to ensure that reservoirs are optimized for multiple objectives, however, rather than for solely hydropower production as is typically the case. The management of hydropower reservoirs to include water supply and flood control increases the potential for conflicts and reduces energy production if reservoir operating levels are lowered (Rydgren et al. 2010). Providing flood control storage means the reservoir must be drawn down to provide flood capture space (according to flood rule curves) at the very time the capacity is most needed to supply the regional energy demand. This is a direct compromise in the hydropower benefits being sought, in terms of energy production and revenue (Harrison *et al.* 2007). Also, water supply risk could increase when reservoirs are lowered for flood control if the basin enters a period of drought after reservoir drawdown. These conflicts may be exacerbated by climate change in river basins such as the MRB, where variability of extreme events is likely to increase (Kundzewicz et al. 2008). If the increase in variability is mainly within a given year (e.g. a more uneven seasonal distribution), reservoir capacity may be sufficient to absorb difference between high-flow and low-flow periods. But, if the between-year variability were to increase, significantly larger storage capacity may be necessary in order to guarantee “firm” capacities at all times (Rydgren et al. 2007).

ICEM (2010) reject the argument that storage reservoirs on the LMB tributaries and on the Lancang mainstream offer substantial flood protection benefits. These reservoirs regulate seasonal flows, reducing wet season and increasing dry season discharges, but are not managed to ensure flood protection during extreme events. They note that when extreme flood events threaten the safety of large reservoirs, operators are likely to pass through most of the flood waters, and that in some cases dam management practices have aggravated the situation by increasing downstream flows to empty storage space ahead of an extreme event. The effective management of extreme flood events would require institutional arrangements between project operators and governments which allow for coordinated multiple-use reservoir management integrated with regional meteorological data and forecasting. ICEM (2010) further argues that the MRB annual (not extreme) flooding cycle is a positive factor on which much of the natural system, fisheries and agriculture productivity depends. There is no need to protect downstream areas from these regular seasonal events, especially as negative impacts of climate change increase in the basin.

The LMB mainstem run-of-river reservoirs would operate near full supply level, and therefore do not have the capacity to attenuate extreme flooding events. LMB run-of-river facilities likewise have limited capacity to provide water supply, and are more sensitive to droughts, thus providing no clear benefits with respect to mitigation of climate change impacts.

Natural or enhanced floodplain storage in the river basin could provide an important alternative to reservoir storage for climate change mitigation (Harrison *et al.* 2007). Agencies responsible for flood control could identify opportunities for securing or rehabilitating floodplains, including the purchase of floodplain easements (Opperman *et al.* 2009). Revenues also could be allocated for improved flood forecasting capacity, enforcement of existing floodplain settlement policies, and effective and well-tested flood warning systems (Beilfuss 2012).

In summary, large-scale hydropower development in the MRB offers significantly lower levels of GHG emissions relative to business-as-usual (fossil fuel intensive) energy development. However, the benefits of hydropower relative to alternative strategies for reducing GHG emissions, through renewable energy sources and demand management, are less clear. Further, although large hydropower reservoirs in the UMB and LMB tributaries have the potential to mitigate climate impacts by providing water supply and reducing the impact of extreme floods and droughts on vulnerable populations, they are currently managed solely to optimize hydropower production rather than provide for multiple objectives. These findings are of particular concern when weighed against the adverse roles of hydropower development in mitigating climate change in the MRB, discussed in the next chapter.

5 ECOSYSTEM SERVICES, HYDROPOWER DEVELOPMENT, AND CLIMATE CHANGE ADAPTION IN THE MEKONG RIVER BASIN

Climate change is affecting all sectors and levels of society (Schneider et al. 2007). Even if global GHG emissions are stabilized relatively soon, the impacts of climate change will persist for decades or longer, and will require adaptation on an unprecedented scale. Adaptation is the process by which individuals, communities, and nations seek to reduce their vulnerability to climate change effects (UNDP 2004). The United Nations Framework Convention on Climate Change reports that the most effective climate change adaptation approaches in developing regions such as the MRB are focused on poverty alleviation, food security, water availability, land conservation, and biological diversity. These factors in turn are critically dependent on the natural resources and processes, or *ecosystem services*, that sustain them. In this chapter, we outline the important role of ecosystem services in the MRB, review the impact of existing and proposed dams on those ecosystem services, and assess the cumulative impacts of climate change and hydropower production on ecosystem services and the capacity for climate change adaptation in the MRB.

Projected impacts of climate change on ecosystem services in the Mekong region include decreasing overall water availability, decreasing food production capacity – especially rice and aquaculture production, increased incidence of extreme floods and droughts, sea level rise and land submersion in the Mekong delta (Snidvong *et al*. 2003, Wassman *et al*. 2004, Eastham *et al*. 2008, Johnston *et al*. 2010; Costanza et al. 2011). According to Johnston *et al*. (2010), for the near future (20 – 30 years) in the Greater Mekong region the impacts of climate change on water resources would likely be smaller than those caused by economic, demographic and environmental changes. Proposed hydropower development can bring larger changes than those caused by predicted climate change and in a shorter time frame (Lauri *et al*. 2012).

5.1 Ecosystem services

Ecosystem services are typically classified into four broad categories: (i) *provisioning services* such as food, fiber, fuel, natural medicines, and freshwater; (ii) *supporting services* such as nutrient cycling, soil formation, and primary production; (iii) *regulating services* such as climate regulation, erosion control, flood regulation, disease regulation, and water purification, and (iv) *cultural services* such as spiritual and religious values, education, aesthetics, and recreation (Millennium Ecosystem Assessment 2005). Collectively, these ecosystem services play a central role in both adaptation to and mitigation of climate change (IPCC 2007; Staudinger et al 2012). Because the poorest countries and the poorest people are most vulnerable to the effects of climate change, sustaining ecosystem services is vital both in our efforts to cope with climate change and to reach the UN’s Millennium Development Goals (2005).

The value of ecosystem services and products in the MRB is enormous. The largest inland freshwater fishery of the world (Hortle 2009), the world's largest export rice production systems (FAO 2013), and one of the most important freshwater biodiversity hotspots on the planet (ICEM 2010), all depend on ecosystem services provided by the Mekong river. The majority of the human population in the MRB lives in rural areas, where their livelihoods depend directly and strongly on products derived from natural ecosystems (MRC 2010, Pearce-Smith 2012). The Mekong River Commission's State of the Basin report (2010) provided a succinct summary of the vast wealth of products and services the Mekong River is offering to its inhabitants. The Mekong provides an ample, year-round flow of freshwater that nourishes life and makes economic activities such as agriculture, fisheries, aquaculture, and transportation, and power generation, possible. Food sources and livelihood activities of rural people are heavily dependent on the Mekong flows and wetlands. Mekong fisheries are extremely important for food security in the region, the most important source of protein and micronutrients for millions of people. More than 240 species of aquatic plants and animals are directly collected from rivers and wetlands for use by rural people. Water-related occupations are mainly farming and fishing, together with various types of jobs that are linked to those two main occupations such as post-harvest processing, marketing and trading, equipment production and repair. Agricultural production, especially rice, in the MRB is responsible for food security for millions of people who not only live in the Mekong countries but also in many other countries of the world. Less known, but of no less importance, are supporting, regulating and cultural services from the Mekong. Wetlands of the MRB, including inland freshwater, brackish and coastal marine systems, are performing many supporting and regulating functions such as habitats for biodiversity, flood control, erosion control, shoreline protection and water purification. River sediment flow is fundamental in maintaining basin's geomorphological processes and ecosystem primary productivity. Long history of human settlement along the Mekong River and its tributaries and the ethnic diversity of the Mekong's dwellers lend themselves to the precious cultural values of the Mekong's riverine landscapes.

Unfortunately, ecosystem services are intrinsically dependent on climate and vulnerable to global climate change. During the twentieth century, climate change has had measurable impacts on the structure and function ecological systems worldwide, and the impacts are expected to increase as climate change continues and perhaps even accelerates (Staudinger et al 2012). These impacts include for example *increased vulnerability and reduced resilience (*about 20-30 percent of all species are at risk of extinction if the global average temperature rises by 1.5 to 2.5 degrees), *decreased agricultural productivity (*some agricultural land will no longer be possible to cultivate, growing seasons will change, and crop production will decrease in many areas), and *decreased fisheries productivity* (reduced marine and freshwater fish stocks) (Schneider et al. 2007).

Making matters worse, ecosystems and the vital services they provide are already under severe threat from many anthropogenic factors other than climate change. The United Nations Millennium Ecosystem Assessment (2005) indicated that 60% of the ecosystem services studied on a global basis are severely degraded and unsustainable at current rates of use. Many factors contribute to this degradation, including increasing human consumption per capita coupled with rapidly growing populations, over-exploitation of natural resources, changing land use and land cover, increasing pollution, and invasive species.

Hydropower production, by altering many physical characteristics of a river basin, is one of the major drivers of degradation, reducing the amount, type and quality of ecosystem services provided by river systems. While dams have made an important contribution to human development, in too many cases an unacceptable and often unnecessary price has been paid, especially in social and environmental terms (World Commission on Dams 2000). Keskinen et al. (2010) argue that reservoir operation and climate change are among the most influential drivers of future hydrological change in the Mekong. Thus, although hydropower is a source of renewable energy that contributes significantly lower levels of GHG emissions than fossil fuel alternatives (Chapter 4), large-scale hydropower development is further exacerbating the impacts of climate change on ecosystem services and reducing the capacity for climate change adaptation. These impacts are described in detail below.

5.2 Impact of hydropower development on ecosystem services

The impacts of hydropower development on ecosystem services worldwide are well-described (World Commission on Dams 2000). Hydropower dams block fish migrations, inundate upstream habitats, and displace human communities. Downstream, the modification of water flow regimes caused by dams is one of the primary causes of the degradation of freshwater ecosystems worldwide (Richter *et al.* 1997). Harrison, Opperman, and Richter (2007), in questioning the sustainability of large-dam hydropower, note “the basic life histories of freshwater organisms – how, where and when they reproduce and grow – have evolved in response to natural flow variations such as seasonal high flows and natural drought periods… when these natural flows are highly altered, populations of freshwater species can plummet or even be driven to extinction.” Hydropower dams store floodwaters for later use, reducing daily flow rates in the high-flow season, including eliminating small floods. They also augment natural low flows in the dry season, when stored water is released for power generation. In some instances, dam releases can cause unnatural high flows at the wrong time of year, washing away riverbank crops or sandbar nests of birds and reptiles. Extreme fluctuations in flow resulting from peak-power production also stress fish and aquatic ecosystems. In addition to changes in the flow regime, dams can heavily modify water temperatures and the downstream transport of sediment, further affecting river ecosystems. All of these environmental impacts can have serious implications for downstream plant and animal communities, as well as human communities dependent upon the goods and services provided by properly functioning river ecosystems.

Impacts on river hydrology

Altering the hydrological connection between rivers and their floodplains fundamentally impacts the composition, structure and function of river systems (Junk et al. 1989). Numerous studies have documented the adverse effects on ecosystem services worldwide of altered hydrological regimes due to large dams and other water resources development, including reduced sediment load and nutrient availability, channel degradation, loss of wetland habitat, altered food chain dynamics, habitat fragmentation, salt water intrusion, disruption of fish migration and reproduction, coastal erosion, and loss of mangroves (Beilfuss 2012). Hydropower development in the Mekong river basin will not be an exception. Various studies have concluded that existing and proposed hydropower dams on the Mekong mainstream and tributaries will alter the hydrological regime, degrading the ecosystem services upon which millions of livelihoods are based (Adamson 2001, Campbell 2009, Hoanh et al. 2010, ICEM 2010, Piman et al. 2012, Rasanen et al. 2012).

Rasanen et al. (2012) demonstrated that the operation of the cascade mainstream dams in China would lead to a new hydrological regime with less seasonal variability in flows and water levels. The 6-dam scenario in the UMB mainstream would cause 34 – 155% dry season flow (December – May) increase and 29 – 36% wet season flow (July – September) decrease at Chiang Saen. Cascade dam operation would also increase the variability of monthly discharge in downstream regions, with highest variability during March-April. Hydrological models predict that Mekong river flows will increase in March by 49% on average at Kratie due to dam operations in China, corresponding to about 1.1 m increase in the average monthly water level. Their study also predicted decreases in flood duration, flood amplitude, and maximum water level and a delay in the onset of flood season. Flood duration would decrease by 58 days in the 3-dam scenario and by 81 days in the 6-dam scenario relative to the 214 day flood duration in the baseline scenario. Flood amplitude would decrease by 3.1 m and 1.8 m under the 6-dam and 3-dam scenario, respectively. The start and end dates of flood season would be shifted later by almost a month in the 3-dam scenario relative to the baseline. Adamson 2001 and Hoanh et al. 2010 indicate similar patterns of change in the hydrological regime, although the projected magnitude of change differs among the studies. Figure 12 shows the general impact of UMB and tributary hydropower development on the annual hydrograph for the LMB.

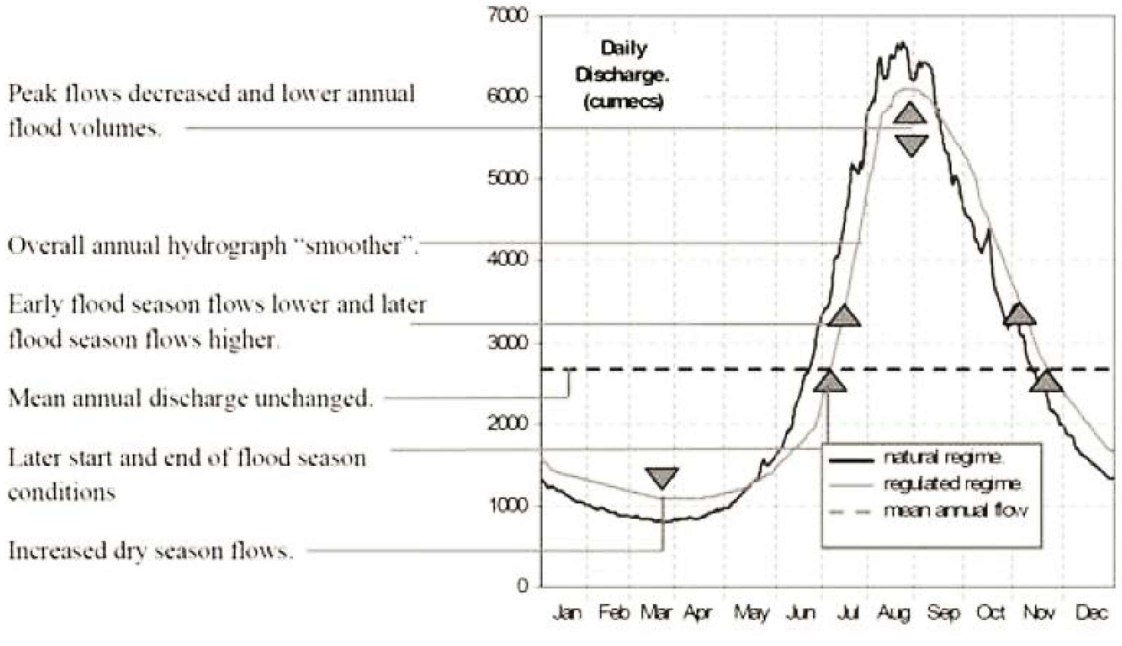

Figure 12. Generic characteristics of the changes to the Mekong hydrograph from UMB and tributary storage hydropower (ICEM 2010).

Stream power is a measure of energy available in a river channel, which has important implications for many aspects of river hydrology and geomorphology. ICEM (2010) estimate UMB dam operation is reducing the Mekong’s stream power by 30%, and that the proposed LMB mainstem dams will further reduce stream power by a substantial amount. The reduction of stream power reduces sediment transport capacity, alters the seasonal cycles of deep pools, degrades river bank stability, jeopardizes fish migration, complicates fishing activities, and increases the risks involved with other uses of the river such as navigation (ICEM 2010).

An increased water surface level upstream of dam sites in the LMB main channel would flood substantial areas of river channel and its associated riverine ecosystems, farm lands, and settlement areas. Changes in water surface levels, both upstream and downstream of dam sites, will complicate irrigation operation and require major re-structuring, relocation, or re-design of hundreds of irrigation facilities (ICEM 2010). Mainstream dam operation would also induce rapid fluctuation in water levels reaching far distances downstream. Hourly spikes of water levels can be 3-6 meters at locations 40-50 km downstream of dam sites and the fluctuations can be much higher in case of emergency water release. It is estimated that some 430,000 people living within 100 km downstream of the LMB mainstream projects would be exposed to rapid fluctuations in water levels (ICEM 2010).

As noted in Chapter 2, the Mekong River is strong flood pulsing system and reductions in the river pulse due to river regulation have adverse eco logical and social consequences. The natural, well-defined transition seasons between the flood season and dry season are particularly important for triggering biological and ecological processes in the riverine and floodplain ecosystems (Baran 2006). Dams on the mainstream and tributaries will alter the timing and duration of these seasons (Adamson et al. 2009, ICEM 2010). Analysis by ICEM showed that with the existing and proposed mainstream dams, the upper reaches of the LMB will no longer experience transition seasons and all reaches between Chiang Saen and Kratie will have shorter transition seasons.

Although most of the concern to date has been focused on the proposed dams on the LMB mainstem, recent studies caution that significant adverse effects are associated with hydropower development on the LMB tributaries as well. Piman et al. (2012) demonstrated that the combined effect of 42 dams on the Se Kong, Se San and Srepok river basins, which contributes 20% of the Mekong annual flow, would cause a 63% increase in dry season flows and a 22% decrease in wet season flows at the outlet of that three-river basin. The magnitude of flow change from this scenario is comparable to those caused by all mainstream dams in the UMB and are larger than potential flow changes induced by the proposed 11 mainstream dams in the LMB. They also argue that the impact of climate change on LMB tributary hydropower and hydropower development is greater than on the mainstem Mekong. Ziv et al. (2012) further noted that many of the proposed dams on the Se Kong, Se San, and Srepok basins would directly affect protected areas important for biodiversity conservation, most noticeably Yok Don National Park (Vietnam), Lomphat Wildlife Sanctuary, Virachey National Park, Moldulkiri protected area (Cambodia) and Xe Pian National Park (Laos).

It should be noted, however, that hydropower development is not the only factor that significantly affects the hydrology of the MRB. Other factors such as large-scale irrigation development, urbanization and deforestation may also have important effects (Adamson *et al*. 2009). War-induced land cover changes were shown to have notable effects on Mekong's runoff in northern and southern Lao PDR (Lacombe *et al*. 2011, Lacombe and Pierret 2013).

Impacts on fisheries and fish diversity

The volume of inland capture fisheries in the LMB is considered the largest in the world, capable of producing around 2.1 million tons of fish annually, roughly 18% of world's freshwater capture fish (Baran & Myschowoda 2009). The economic value of LMB fisheries is estimated as $2.2-$3.9 billion USD within fishing communities and $4.3 to $7.8 billion USD in retail markets (Hortle 2009). This value exceeds the total revenue from electricity generated by all proposed mainstream dams in the LMB, estimated at 3.8 billion USD per year (ICEM 2010). Furthermore, fish and other aquatic animals are significant components in the diets of people living in the LMB, accounting for 47%−80% of the total animal protein consumed (Hortle 2007). Many studies have ascertained the importance of capture fisheries in nutrition, food and livelihood security for millions of people in the LMB (Hortle 2007, Barlow et al. 2008, Baran & Myschowoda 2009, Dugan et al. 2010).

Hydropower dam construction on the mainstem Mekong and its tributaries will have dire consequences for LMB fisheries. Forty to seventy percent of fish catch in the Mekong basin depend on fish species that migrate long distances along the mainstream and into the river's tributaries (Dugan et al. 2011). The strategic environmental impact assessment for the proposed mainstream dams in the LMB estimated a loss of $476 million USD per year in inland fishery, not including potential loss in coastal fisheries in the Mekong Delta which is expected to be substantial (ICEM 2010). The SEA also emphasized that loss in capture fisheries would lead to decline in nutritional health, especially in Laos and Cambodia where up to 30% of national protein supply would be at risk. An assessment conducted by the Mekong River Commission estimated that nearly 4.4 million people would be affected by reduction in fishery productivity as a result of hydropower development under the *Foreseeable Future Scenario* (MRC 2011a). Hydropower reservoirs, on the other hand, can help increase fishery production through fish farming. ICEM's study (2010) pointed out, however, that reservoir fish farming contributed little (as much as 10%) to compensate for the loss of capture fisheries caused by LMB mainstream dams. Moreover, reservoir fish farming tend to favor non-native fish species, for example *Tilapia*, which may increase the risks associated with invasive alien species.

Fisheries in the lower Mekong basin also can be negatively affected by factors not related to hydropower dams, such as over-fishing and habitat loss (Hortle 2009). Fish catch in the LMB is expected to decline in the near future even in development scenarios that do not involve hydropower development in the Mekong mainstream, but the magnitude of loss is much smaller compared to those with mainstream dams (ICEM 2010).

Aquaculture production also contributes significantly to the economy of Lower Mekong countries, especially Vietnam. On average between 2005-2007, the volume of freshwater aquaculture fish production in the four LMB countries was 1.8 million tons/year, of which 1.2 million tons was from the Mekong Delta in Vietnam (Baran 2010). The General Statistics Office of Vietnam reported 1.66 million tons of fish and 0.37 million tons of shrimp produced by aquaculture in the Mekong Delta in 2011 (http://www.gso.gov.vn/, accessed March 15, 2013). The cumulative impact of upstream dam development, sea level rise, and other effects of climate change on Mekong Delta aquaculture requires further studied. Likewise, the cumulative impacts of hydropower development and climate change on fish populations, species diversity and fishery productions are still poorly understood.

Ichthyofauna is the component of biodiversity that would be most directly affected by hydropower development in the Mekong basin. Freshwater fish diversity in the LMB is outstanding. The Mekong river is ranked second in the world, after the Amazon river, in terms of fish species diversity, with 781 fish species being scientifically verified and recorded in Fishbase (www.fishbase.org) – a global fish database (Baran 2010). At least 850 freshwater fish species are known to occur in the MRB; more than 1,100 fish species when coastal and marine species associated with the MRB are included (Hortle 2009). In the last decade alone, more than 279 new species of fish have been discovered for the Mekong basin (WWF 2009). The Tonle Sap Lake, with 197 freshwater fish species recorded, has the highest freshwater fish diversity in Asia and the fourth highest in the world (Baran 2010). Endemism is also high - 22%, 29% and 14% of the fish population in the upper, middle and lower reaches of the Mekong, respectively, are endemic (Baran 2010).

Hydropower dams affect Mekong fish biodiversity through modifications of river flow, sediment flux, magnitude and timing of floods, loss of riverine and floodplain habitats, and the barrier effect of dam structures on fish migration (Baran & Myschowoda 2009, Baran 2010, Halls & Kshatriya 2009, ICEM 2010). The proposed mainstream dams in the LMB would cause the most dramatic disruption to fish migration. Analysis by Baran (2010) showed that in 2000 with 16 hydropower dams on the tributaries, 20.6% of the LMB is inaccessible to fish migration. With all 11 mainstream dams in operation, however, fully 81.3 % of the watershed will be obstructed and inaccessible, with fish unable to migrate upstream of Kratie. The reservoirs of proposed mainstream dams would eliminate or greatly alter many riverine wetland types, especially the deep pools which are critical habitats not only for many commercial fish species but also for several charismatic aquatic animals of the Mekong such as the Irrawaddy dolphin (Viravong et al. 2006). Recent studies suggest that considerable land and water resources would be needed in the MRB to compensate for lost fisheries with livestock production (Orr et al. 2012).

Impacts on agricultural production

Hydropower development is predicted to have significant adverse impacts on agricultural production in the MRB. In the upper to middle reaches of the river, ICEM (2010) estimated that some 150,000 hectares of river gardens, farm lands and irrigation structures would be directly inundated by the reservoirs of proposed mainstream dams. Further downstream, river regulation will impact the two most important agricultural production areas in the MRB, the Tonle Sap basin and the Mekong Delta. These areas also are among the most densely-populated areas in Southeast Asia. Changes in flow regime, timing and duration of flood, and reduction in sediment load will greatly affect agricultural production (ICEM 2010). Several studies have investigated the sediment trapping effect of mainstream hydropower dams on the Mekong basin (Kummu & Varis 2007, Walling 2010, Kummu et al. 2010, Xue et al. 2011, Wang et al. 2011), concluding that dams will greatly reduce sediment loads delivered to downstream areas.

ICEM (2010) estimated that up to 75% of suspended sediment load in the Mekong river at Kratie (160-165 million tons/year) would be trapped by dams on the Mekong mainstem and tributaries, including a 50% reduction associated storage dams in the UMB and the 3-S basin, and an additional 25% reduction associated with proposed LMB mainstem dams (ICEM 2010). The same study also estimated that the amount of nutrient supply to Mekong floodplains and delta would decrease from the current estimate of 26,400 tons/year to about 6,600 tons/year, a 75% reduction. The reduction in nutrients carried in river sediments will adversely impact the productivity of both natural and man-made ecosystems in the downstream areas, especially the Cambodia floodplains, the Tonle Sap Lake, the Mekong Delta, the river-mouth estuary, and the near-shore marine area. This will in turn require a substantial increase in the use of chemical fertilizers to sustain crop yields, resulting in higher cost of crop production and increasing risks of surface water pollution.

Hydropower development has the potential to contribute positively to agriculture production, most notably through reservoir-based irrigation, especially in drought-prone regions. As discussed above, this the benefits to irrigation depend largely on the degree to which hydropower production is development as part of multi-objective criteria and priorities. Analysis by Lacombe *et al*. (2011) showed that hydropower development would provide sufficient water for irrigation in the Vientiane Plain, Lao PDR, and that without dams the targeted irrigation development could not be reached because insufficient water during the dry season of dry years.

Impacts on wetland ecosystems

The LMB is particularly rich in wetland habitats, from small, seasonally-inundated depressions to some of the world's largest floodplains, with diverse hydrological conditions, water chemistry, and vegetation characteristics giving rise to a tremendous diversity of plant and animal communities. Wetlands provide a range of important provisioning and regulating services, including but not limited to flood mitigation, water supply during droughts, ground water recharge, and surface water purification, and fisheries and wildlife habitat. Key wetland systems of the LMB that would be strongly affected by hydropower development include riverine wetlands along Mekong mainstem and tributaries, the Tonle Sap Lake system, and the Mekong Delta.

Riverine wetlands

ICEM (2010) estimated that the proposed LMB mainstream dams would convert a 996 km reach of the Mekong river from riverine to lacustrine (reservoir). Reservoirs would occupy 55% of the total length of Mekong between Chiang Saen and Kratie, and inundate 1,370 km^2 of riverine wetlands. Species of concern threatened by river regulation include the Irrawaddy dolphin *Orcaella brevirostris* in the Siphandone – Stung Treng area (Stacey & Leatherwood 1997) and the Siamese crocodile *Crocodylus siamensis* in Laos (Bezuijen et al. 2013).

Tonle Sap Lake

Increasing dry season water levels resulting from upstream hydropower operation are considered the biggest threat to the Tonle Sap ecosystems. According to Kummu & Sarkkula (2008), dry season water levels are expected to increase by 0.15 – 0.6 m, increasing the area of permanent lake by 17–40% decreasing the area of seasonally inundated floodplain by 7–16%. The authors estimated that a 0.6 m increase in dry season water level would lead to total extinction of gallery forests surround the lake and permanently flood up to 83% the area of Boeung Chmar (a *Wetland of International Importance* under the Ramsar Convention) and 42% of the three core zones of the Tonle Sap Lake Biosphere Reserve.

Mekong Delta

The reduction in river sediments and nutrients reaching the Mekong Delta associated with upstream reservoirs will alter the geomorphology, ecology, and biodiversity of the Mekong Delta (ICEM 2010). As the Mekong's flow, flood pattern and sediment load are modified by upstream development and by climate change, the impacts of these changes to important wetlands for biodiversity conservation in the Mekong Delta such as Tram Chim (open and forested floodplain) and Mui Ca Mau (mangrove forest) national parks, are still poorly understood.

5.3 Cumulative impacts of hydropower development and climate change on ecosystem services

Few studies have examined the cumulative impacts of hydropower development and climate change in the MRB, and have mainly focused on the impacts of climate change on river hydrology and flooding. Hoanh et al. (2010) and MRC (2011a) studied the combined effects of basin development, including hydropower and climate change on the hydrology of the Mekong system using the results of one GCM (ECHAM4) with the A2 and B2 climate futures. Mainuddin et al. (2010) also used ECHAM4 under A2 and B2 scenarios to assess the combined effects of basin development and climate change on the Mekong's flow regimes, floods, fisheries and agricultural productivities. Lauri et al. (2012) assessed the cumulative impacts of reservoir operation and climate change, using multiple, downscaled RCMs with the A1b and B1 climate scenarios. Most recently, Ziegler et al. (2013) assessed the cumulative impact of dams and climate change on ecosystem capacity to regulate disease in the Lower Mekong River.

Mainuddin *et al*. (2010) found that Mekong flow change due to combined effects of development and climate change would cause minimal impacts on fish biomass of the Tonle Sap Lake. The authors acknowledged that this result did not take into account other factors which may have important effects on fisheries such as fish passage and nutrient blockage by hydropower dams. Mainuddin *et al.* (2010) also found that under A2 and B2 climate scenarios, yield of rainfed rice may increase 8-28% in Laos and Thailand but may decrease 11-14% in some part of Cambodia and in the Mekong Delta in Vietnam. For irrigated rice, yield may increase through the basin between 15-28%. Higher rice yield was explained as mainly due to increase in CO_2 concentrations in the atmosphere. The analysis did not, however, take into account the impacts of sea level rise and other extreme events such as big floods, extreme droughts, heavy storms, which might have adverse effects on rice production.

Results of modeling analysis by Lauri et al. (2012) suggested that the impact of hydropower on some hydrological characteristics of the Mekong River, such as monthly discharge, flood peaks and dry season flow, are clearly larger than those caused by climate change. Their conclusions concur with those of other studies (Hoanh et al. 2010; Piman et al. 2012). The authors found a large variation in projected river discharges under different GCMs, even the direction of changewere uncertain. This modeling result suggested it may be possible that some flow-related impacts of climate change would be in similar direction to those caused by hydropower reservoir operation (reducing high flow and increasing low flow)not in opposite direction as suggested some other studies (for example Vastila *et al*. 2010). The authors concluded that climate change increased the level of uncertainty in estimating the impacts of hydropower dams on the Mekong's environment and emphasized the importance of assessing the cumulative impacts of these two drivers of change.

Morin (2012) described the causal links between climate, and other environmental influences, and the ecology of vector-borne diseases. Ziegler et al. (2013) noted that global warming is expected to reduce the capacity of ecosystems to control disease, magnifying the effect of dam development on malaria, dengue fever, and other diseases in the MRB.

Cumulative impacts of hydropower development and climate change are likely the most severe in the Mekong Delta and Tonle Sap basin, where the combined effects of all upstream water resources development converge with the regional and local impacts of climate change and sea level rise.

Mekong Delta

The Mekong Delta is particularly at risk of climate change-induced sea level rise (Wassman et al. 2004, Eastham et al. 2008, Doyle et al. 2010). Analysis by the U.S. Geological Survey (Doyle et al. 2010), taking into account the effect of land subsidence, estimated the sea levels would rise during the period 2010 – 2100 at the rate of 4.3 mm/year under scenario B1 (best case) to 5.5 mm/year under scenario A1FI (worst case). According to the study, all areas of the Mekong Delta that are less than 0.5 m above the current sea level are expected to begin inundation by 2035 and be completely submersed by 2068.

Khang et al. (2010) examined the combined effects of salinity intrusion and flooding on rice cultivation, resulting from sea level rise and altered Mekong discharge associated with climate change (scenario A1b). They found that although there may be an increase in water availability for irrigation if upstream discharge increases, the benefits of irrigation would be outweighed by the costs of more severe flooding. The area suitable for triple rice cropping would decrease from 31% to 5%, and the area suitable only for single rice cropping would increase from 21% to 62%. The authors assessed the vulnerability of rice production to climate change based on projected changes in the duration of rice cultivation, and classified 67% of the total land area in the Mekong Delta as medium (31%) to high (36%) vulnerability.

Almost 75% of the Long Xuyen Quadrangle (4,900 km^2), southwest of the Mekong Delta in Vietnam, would be subject to medium to very high flood risk by 2050 as a result of sea level rise (Dinh et al. 2011). Large urban centers in the Mekong Delta also face much higher flood risk. For example, Can Tho – the largest city in the Mekong delta with more than 1.2 million dwellers – could experience an increase of 0.5-1.5 m flood depth under combined effects of sea level rise and urban growth by mid-21st century (Huong & Pathirana 2013).

Vastila et al (2010) predicted a sea water level rise of 31 cm in the Mekong delta area by 2045, averaging 7-8 cm increase per decade. The study predicted an increase in total flooded area, maximum water depth, and flood duration, with the flood season likely to begin earlier and end later and peak floods likely to occur later, relative to the present. Potential negative impacts of these shifts include a reduction in fertile land area and crop production, and increased damage to infrastructure and floodplain vegetation. Potential positive effects include increased water availability and primary productivity. The predicted changes in MRB discharge associated with climate change and water resources development are of approximately the same magnitude, but occur in the opposite direction. The authors note that these changes do not cancel out, however, because they operate at different time scales - the impacts of upstream hydropower development are immediate, whereas the impacts of climate change are more gradual and variable.

Le et al. (2006) predicted that decreased flood peaks and increased tidal pumping as a result of dam construction in the UMB would silt the Bassac River estuary, particularly in the area between Can Tho City and the river mouth, narrowing the thalweg width in half and raising the channel bed by 2 m within 30 years. The siltation of the river mouth would further raise peak flood levels locally in the delta by about 2 m. It is unclear whether the study accounted for reduced sediment loads downstream of UMB dams.

A flood modeling study by Van et al. (2012) showed no significant difference in flood extent and duration in the Mekong delta under future sea level rise scenarios with and without water resource development upstream of the Mekong river basin. Lower river discharge in the wet season due to upstream development would shorten flood duration by only four days on average. The study found that sea level rise would have much stronger effects on the flood pattern and the impact is not uniform throughout the Mekong Delta. Flood extent would be larger and flood duration longer in the coastal and lower part of the delta (Ca Mau peninsula) while the changes in the upper part of the delta are much less pronounced. These changes in flood patterns, coupled with an increase in salt water intrusion, would severely affect agriculture and aquaculture production in the Ca Mau peninsula as well as elevating the risk of infrastructure damage and the associated maintenance cost.

Climate change is expected to result in more erratic dry season rainfall and increased drought in the delta region (ICEM 2010, Johnston et al. 2010). These changes could impact native vegetation communities of seasonally inundated wetlands such as those at Tram Chim National Park in the Mekong Delta and the flooded forests of the Tonle Sap Lake (ICEM 2011), further worsened by increased river discharge in the dry season due to upstream dam operation. However, the cumulative effects of these changes have not been studied.

Tonle Sap Lake

Arias et al. (2012) examined the impacts of upstream water resources development and of climate change on Tonle Sap Lake’s natural and man-made ecosystems. The study found opposite trends in flood extent at similar magnitude: upstream development expected to reduce flood extent by up to 1,200 km^2 while climate change expect to increase flood extent by up to 1,000 km^2. The implications on wetland habitats of the Lake are projected to be somewhat different. Water development would favor the expansion of rain-fed rice paddies and other crop lands while decreased the areas of seasonally flooded shrub-lands and grasslands. Climate change, on the other hand, could enhance optimum conditions for seasonally flooded habitats. The overall impact, however, points to the common trend of increasing open water areas and decreasing areas of gallery forests. The authors emphasized that the consequences of shifting in habitats would lead to major changes in sedimentation, nutrient cycling, primary productivity, fish production and eventually livelihoods of local inhabitants.

Other wetlands

Droughts and increased evaporation associated with higher temperature would reduce dry season water availability in small wetlands of open dry forests in Southern Laos, Northern Cambodia, and the Central Highland of Vietnam.

5.4 Gaps in knowledge

The full range of ecosystem services provided by the MRB have not been adequately quantified, especially in terms of their economic value to basin communities and the broader economy of the MRB and Southeast Asia. As a result, the impact of lost ecosystem services (with the notable exception of freshwater fisheries) are typically not accounted for in cost-benefit analyses of development scenarios. These studies are essential to estimate the real cost of hydropower generation in the MBR and provide objective information for decision makers, investors, and other stakeholders to evaluate different development scenarios.

The impacts of reduced sediment and nutrient loads caused by upstream hydropower development on downstream geomorphology, ecosystem structure, diversity, and productivity, and economic production systems (e.g., agriculture and aquaculture), especially in the Tonle Sap and the Mekong Delta regions, are poorly understood and require more detailed study.

The few impact assessment studies of hydropower development and climate change that have been conducted for the MRB have followed a highly sectoral approach—assessing hydrology, fisheries, and agriculture in isolation, for example (Keskinen et al. 2012). Future studies of cumulative impacts should focus on the full range of economic and social sectors, with wider spatial coverage to include multiple development projects affecting the system.

Finally, it is important to note that hydropower development and climate change are not the only drivers of change in the MRB. Other important factors that alter Mekong hydrology and water- resources include large-scale irrigation development, land use change (e.g., deforestation), industrialization, and urbanization (Hoanh et al. 2010, Johnston et al. 2010, Lauri et al. 2012). These factors must be considered in any assessment of the cumulative impact of river development and climate change on MRB ecosystem services.

In summary, ecosystem services benefit millions of people in the MRB. Although the magnitude and timing of impacts may differ, the combined effects of hydropower development and climate change will reduce these benefits considerably. The rural poor are especially vulnerable to these changes because their livelihoods are more directly dependent upon ecosystem services. As pointed out in previous chapter (Chapter 4), hydropower development in the MRB has a good potential in climate change mitigation through reducing GHG. On the other hand, it can also cause great losses in natural products and ecological services the Mekong River is offering. Reduction in captive fisheries, especially in Laos and Cambodia due to hydropower development would affect the livelihood and food security of millions of people. Maintaining ecosystem services, protecting livelihood bases and improving standard of living are among the main strategies for climate change adaptation (Lawler 2009, MRC 2009a, Keskinen *et al*. 2010). Reducing the availability and quality of ecosystem services would negatively affect people’s livelihoods, jeopardize their standard of living and render Mekong riparian communities with much less capacity to cope with climate change in the future.

6 RECOMMENDED RESEARCH AND FURTHER ACTION

The previous chapters identified gaps in knowledge that limit our understanding of the interactions between climate change, hydrological systems, hydropower production, and the ecosystem services that sustain life in the MRB. Below, we provide the highest priorities for gap-filling research, modeling, and monitoring to resolve these uncertainties. Of particular importance are improving climate change projections and quantifying the impact of climate change on certain key hydrological processes relevant to hydropower development, advancing hydrological models to more deeply incorporate land use change, increasing climate variability, and other challenges, modeling hydropower production under these climate change scenarios, and assessing the cumulative impacts of hydropower and climate change on ecosystem services, and the role of alternative, cleaner sources for meeting regional energy demand.

6.1 Gap filling research, modeling, and monitoring

Improving climate change projections of relevance to MRB hydropower planning

Further climate change modeling at the MRB sub-basin level is needed to more clearly define the trends and ranges of climate change and extreme events that need to be incorporated into hydropower development plans and a variety of sectoral adaptation plans. Rapid development is occurring on MRB tributaries with very distinct climatic characteristics, and GCMs and even MRB basin-scale RCMs are inadequate for water resource planners and managers at the local level. As noted in Chapter 3, although temperature simulations are relatively consistent between GCMs, projections of future precipitation from different GCMs are inconsistent in magnitude and even the direction of change, resulting in very low confidence in projections of future runoff for hydropower planning purposes. Further high resolution RCMs must be developed, at the sub-basin level. Uncertainty resulting from different RCM downscaling techniques is generally smaller than from different GCMs (Prudhomme and Davies 2009).

Climate models must predict climate change over the 30-40 year financial-planning horizons of most relevance to MRB developers (Rydgren et al. 2007), in addition to long-term climate trends that affecting reservoir safety and operation over the life of the project. Projections should be based on ensemble model evaluations (e.g., Kingston et al. 2011), based on emission scenarios that encompass a range of futures that include more extreme emissions scenarios that better match current observed phenomena than the means of a range of scenarios. This information would greatly facilitate the utilization of research findings by hydropower operators on time scales that are relevant from an economic/financial point of view.

The highest priority for further climate modeling is to capture the high level of natural, temporal variability in the MRB, especially changes in the frequency and intensity of extreme events (e.g., Johnston et al. 2010). Allan and Soden (2008) suggest that climate models may be underestimating future projections of extreme weather events. Lauri et al. (2012)

note that although climate change is known to have increased the number of extreme events on a global basis (Coumou and Rahmstorf 2012), the origin of these changes in variance in the MRB is poorly understood. They note that flow variance in the Mekong has been linked to factors including the Western Pacific Monsoon (Delgado et al. 2012) and El Nino-Southern Oscillation (ENSO) (Ward et al. 2010; Rasanen and Kummu 2012), both of which are known to be inter-related and vary on decadal scales (Torrence and Webster 1999; Wang et al. 2008). There are also other factors affecting the hydrology in the region, such as Indian Ocean Dipole, Madden-Julian Oscillation, Quasi-Biennial Oscillation, decadal cycles, and tropical cyclones (Singhrattna et al. 2005; Yongqin and Chappell 2009), but their role in the Mekong region is poorly understood. Lauri et al. (2012) suggest that climate change projections based on GCMs/RCMs should be analyzed together with long-term historical (paleo-climatological) data.

Quantifying impact of climate change on key hydrological processes in the MRB

Recent research has significantly advanced our understanding of some of the key hydrological processes in the MRB in relation to climate change, hydrological systems, and hydropower development. Future research is needed to quantify the following system processes, ranked in order of highest priority:

- Runoff response to land use change, including deforestation and large-scale irrigated agriculture development, including projected changes in land use associated with climate change impacts and effect of climate change adaptation on erosion and sediment yields;
- Reservoir evaporation and basin evapotranspiration under future climates, especially in the UMB and more arid portions of the LMB where evaporative losses from reservoirs may represent a significant proportion of annual or seasonal inflows. Evaporative water loss from the Kariba Reservoir in Zambia, for example, is approximately 16% of total inflows (Beilfuss 2012).
- Timing, magnitude, and duration of runoff associated with more frequent extreme events, including floods and droughts. This includes sub-daily weather events in response to climate change, which are critical for assessing the impact of extreme precipitation on river flow events (Xu and Yang 2012).
- Peak flows and winter flow conditions corresponding to a shift in UMB winter precipitation from predominantly snow to rain;
- Hydrological response to increased tropical storms;
- Groundwater contribution to MRB baseflows, and the impact of changing climatic conditions on groundwater recharge, including the extreme floods and droughts.
- Water quality changes of relevance to hydropower management, especially the impacts of extreme events on sediment transport (Bates et al. 2008).

Furthermore, existing monitoring network and data are insufficient to calibrate and verify hydrological models of the MRB. A long-term commitment to monitoring key hydrological variables associated with climate change is needed, at the sub-basin level. This especially includes maintaining and expanding monitoring networks for temperature, rainfall, evaporation, and river stage and discharge. Specific focus should be given to improving knowledge and confidence with respect to the relationships between climate change and river discharge. Monitoring data and feedback also is vital to the adaptive management of climate change impacts.

Advancing hydrological models for the MRB

GCMs do not resolve the hydrological cycle at a level of detail that is suitable for hydrological applications (Bergström et al. 2001), and considerable effort has been invested in recent years to downscale GCMs for regional application in the MRB. Several hydrological models have been developed to project the flow changes under different climate and development options in the MRB, including the SWAT hydrological model, the IQQM basin simulation model, and the hydrodynamic ISIS model (TKK and SEA 2009; Hoanh et al. 2010; Thompson et al. 2013). The highest priorities for future hydrological modeling in the MRB include the following:

- Incorporating scenarios of land cover change in hydrological models, including climate-driven changes, and their influence on projected run-off. Coupling climate models with the land-use changes such as deforestation or expanded irrigation is necessary to evaluate projected changes in runoff associated with future river basin development. Intensification of forest utilization in the MRB will likely increase further the already high rate of deforestation, for example, which could lead to the loss of much of the original forest cover by 2100 (Sodhi et al. 2004, Cruz et al. 2007).
- Incorporating potential thresholds of climate change impacts on hydrology and hydropower development, which trigger non-linear responses, must be considered in model development, including increased magnitude of extreme events that could threaten hydropower structures.
- Modeling of the large range of climate variability across the MRB (Cruz et al. 2007). Even at a coarse scale, runoff from rainfall and snowmelt in the UMB and from intense rainfall over the Laos highlands originate from two distinct atmospheric processes. Contrasting climate trends and changes in the relative importance of different hydrological processes may occur in different sections of the basin (Kingston et al. 2011).
- Linking groundwater with surface water models. Despite its potential significance, MRB baseflow has received little attention in climate change models relative to surface water resources.

Modeling hydropower production under different climate change scenarios

Sophisticated efforts to couple climate change models with hydrological simulation models have been undertaken (e.g., Hoanh et al. 2010, Vastili et al. 2010, Kingston et al. 2011, Lauri et al. 2012). No models have been developed to quantify the impact of climate change on MRB hydropower production, however, even at course spatial and temporal scales. The highest priority for future modeling efforts is to generate runoff scenarios using deterministic hydrological models that can account for non-linear dynamic responses, focused on quantity (annual volumes), seasonal distribution, and variability as the main outputs for hydropower management. Economic and risk analyses normally applied to hydropower development projects should be conducted based on model outputs, and used to guide operational and/or structural design changes required to accommodate climate change realities, including but not limited to firm power contracts, spillway capacities, and outlet structures.

Assessing the role of hydropower relative to other energy alternatives in climate change mitigation

The relatively low GHG emissions generated by hydropower dams are favorable to non-renewable energy sources such as oil, gas, and charcoal. However, given that considerable social and environmental impacts of climate change are exacerbated by large dams, a comprehensive regional assessment of energy and climate change mitigation is needed. A high priority for further research is to assess the degree to which alternative energy strategies – such as energy efficiency improvements, renewable resources such as biomass, solar, wind, geothermal resources, and more efficient and cleaner transport – can meet MRB energy demand while sustaining the water systems and ecosystem services that are vital to life in the basin and foster climate change mitigation. Important emerging tools for this analysis include the Stockholm Environment Institute's recently developed link between their water resources model WEAP and energy model LEAP to assess the hydrological implications of different energy generating scenarios (*G. Lacombe pers. comm.*).

Assessing cumulative impacts of hydropower and climate change on ecosystem services

There is an urgent need for comprehensive studies that assess cumulative impacts of river basin development and climate change in the MRB, as an alternative to the current practice of undertaking "piecemeal" studies that examine different economic sectors or ecosystems independently of one another. Such an approach requires well-orchestrated, interdisciplinary research teams who may represent different schools of thought, employ different research methodologies, and tackle research issues from various perspectives on a comparative basis. Time scales must be considered carefully in cumulative assessment studies, as the current pace of water resource development far exceeds the rate at which climate change impacts are occurring in the MRB. The capacity of local communities to adapt to environmental changes also will change over time. Comprehensive studies also must take into account other important drivers of change in the MRB, including large-scale irrigation development, land use change, industrialization and urbanization.

The highest priorities for further research on the impact of hydropower and climate change on MRB ecosystem services and climate change adaptation include:

- *Sediment/nutrient dynamics. C*omprehensive studies of the sediment/nutrient dynamics in the Mekong are needed to complement the existing detail of the hydrological dynamics of the system. These studies should be extended to cover the marine sediment plume, coastal erosion, and the transport of nutrients into the floodplain. Critical problems to address include how changes in river sediment load, river flow and sea level rise associated will hydropower development and climate change will affect Mekong delta formation processes, and how hydropower and climate change will affect the dynamic balance between sedimentation and land subsidence (both natural and human-induced), the stability of the mangrove belt, and the biological productivity of estuaries and off-shore marine environment.
- *Aquatic biodiversity.* Cumulative assessment of the impacts of hydropower and climate change on aquatic habitats and species, including freshwater, coastal and marine, must be carried out such that effective protection measures for critical habitats and biodiversity hotspots can be incorporated into MRB development and climate change adaptation plans. The on-going study on the impacts of climate change on wetlands of the LMB is an important first step (ICEM 2011).

- *Riparian communities*. Social scientists must examine the dependence of riparian communities (especially those that might be impacted by mainstream dams) upon the natural resources of the Mekong, including fisheries, water resources, and river bank gardens, to provide baseline information to formulate alternative livelihood and poverty alleviation strategies under future climate and development scenarios.
- *Risks to food security*. Comprehensive studies are needed to assess the risks of hydropower and climate change to agricultural, fisheries, and overall food security, aimed at providing science-based strategies for mitigation and adaptation.
- *Risks to health and disease.* Scientists must assess the cumulative risks of global warming and dam development on the disease load in the MRB, and provide clear strategies for public health adaptation and mitigation.

6.2 Hydropower Risk and Uncertainty in a Changing Climate

This scoping study has identified important risks and uncertainties associated with the impact of climate change on future hydrological conditions and hydropower production in the MRB, most notably the considerable uncertainty associated with projecting the magnitude and direction of precipitation change and the volume and timing of runoff, and the increased variability of annual hydrological conditions - especially the frequency and intensity of extreme floods and droughts. Climate change poses a difficult challenge for water resources development and management by introducing uncertainty in future hydrological conditions, and making it difficult to detect underlying trends in hydrological time series (Wilby 2006). Development decisions are being made before it is clear how and at what rate hydrological regimes are changing. Water management in the face of climate change therefore needs to adopt a scenario-based approach (Beuhler 2003; Simonovic and Li 2003). However, there are often large differences in impact between scenarios, requiring that analyses be based on several scenarios with clear knowledge of future trends. Ideally, water managers need information on the likelihood of defined outcomes occurring in order to make risk-based decisions, although our current level of knowledge is insufficient to associate different scenarios with probabilities (e.g., Jones and Page 2001).

To help cope with some of the uncertainty, ways are needed for hydropower owners to assess climate change in terms of an adaptive risk management (Rydgren et al. 2007). What are the expected consequences and what level of risk is acceptable? Climate science is making progress in the coming future by providing more quantitative estimates of the likelihood of certain levels of change (e.g. ENSEMBLES-Project 2004-2009). However, this will still take some time in coming, and will still only be in terms of conditional likelihood (i.e. given a certain emissions scenario). Establishing which pathway world development will take and thus the future levels of CO2 is an even more open issue.

Given the magnitude of projected climatic changes and the importance of water for socio-economic development throughout the region, as well as hydropower, there is a clear need for improved understanding of the potential impacts of climate change on existing and planned water infrastructure (Kingston et al 2011). Current water management practices may not be robust enough to cope with the impacts of climate change on hydropower in addition to water supply reliability, flood risk, health, agriculture, and aquatic ecosystems. In many locations, water management cannot satisfactorily cope even with current climate variability, so that large flood and drought damages occur. Improved incorporation of information about current climate variability into water-related management would assist adaptation to longer-term climate change impacts. Climatic and non-climatic factors, such as growth of population and damage potential, would exacerbate problems in the future (Bates et al. 2008)

Our findings support the conclusions of the Strategic Environmental Assessment team for the MRB (ICEM 2010), in recommending that mainstream dams should be deferred for a period of ten years (strategic option 2) during which critical studies are undertaken to ensure sound decision-making about the future of hydropower development in the basin. In particular, basin authorities and stakeholders must develop better approaches to managing hydropower with increased uncertainty, building in flexibility to system design and operation. In addition to allowing for the priority research, monitoring, and modeling needed to *make informed decisions about MRB hydropower development,* the deferment period should include a comprehensive undertaking of feasibility studies for MRB development alternatives that are the most robust to climate change risks and impacts. ICEM (2010) noted partial in-channel, diversion and other innovative systems for tapping the power of the mainstream in ways which do not require dams across the full breadth of the river channel. Pittock & Hartmann (2011) describe additional risk-management approaches, such as upgrading existing infrastructure; investing in infrastructure that is reversible or can be used under a range of conditions as climate changes; building larger safety margins in infrastructure to cope with extreme events; promoting ‘soft’ (non-infrastructure) adaptation strategies, such as investing in floodplain restoration, rather than infrastructure for flood control; and reducing decision-time horizons for more rapid and incremental responses, such as the addition of smaller and decentralized infrastructure. Assessment of design implications for mainstream projects for risk of increased range in flow and incidents of extreme events is especially critical.

We recognize that hydropower development in the MRB is moving forward rapidly. A cascade of mainstream dams has been constructed on the upper Mekong, numerous MRB tributary dams are in operation, and the Xayaburi Dam is now under construction on the lower Mekong mainstream. Nonetheless, there is still time to influence the design and operation of hydropower facilities in the MRB. We urge caution with taking a “business as usual” approach to hydropower development based on historic climate and flow data that is no longer valid, and traditional design criteria that do not allow sufficient flexibility to manage hydropower with heightened uncertainty. Deferment would allow for critical research on the interface between climate and water, leading to an improved understanding and estimation, in quantitative terms, of climate change impacts on freshwater resources and their management. It would enable credible projections that are essential to the design and management of hydropower projects. And, most importantly, it would fulfill the pragmatic information needs of water managers who are responsible for managing and adapting their infrastructure to a future that will differ markedly from the past.

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